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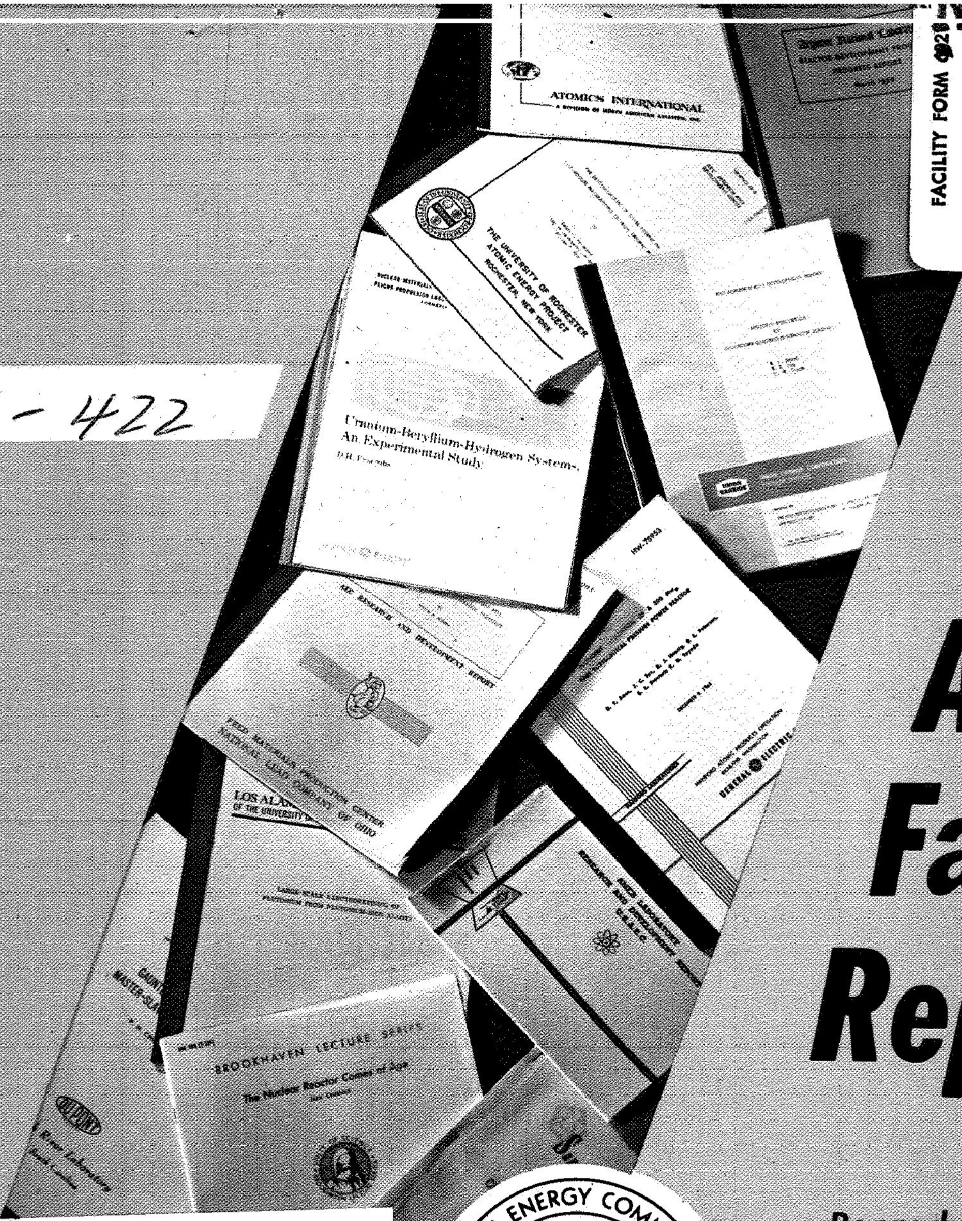

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LABORATORY FOR NUCLEAR SCIENCE

PHYSICS PROGRESS REPORT

October 1, 1967

M. I. T. -2098-422

Researches reported herein have been supported by and large by the Atomic Energy Commission through AEC contract AT(30-1)-2098 and in part by separate contracts and grants with the Air Force Office of Aerospace Research (contract AF19(628)-2389), the National Aeronautics and Space Administration (contracts NASw-37, NASA-2053, NAS5-3205, grant number NsG-386) and the National Science Foundation (grant number G-19728). The work of the Laboratory's Chemistry groups under Atomic Energy Commission contract AT(30-1)-905 is now reported separately.

This is the seventy-first progress report of the Laboratory for Nuclear Science at the Massachusetts Institute of Technology. Progress reported covers the period for Physics from October 1, 1966, to October 1, 1967.

TABLE OF CONTENTS

COSMIC RAY GROUP

I. X-Ray Astronomy

A. Balloon-Borne Experiments

Activity in this area has continued at a high level during the past six months. In general, the program has been to exploit to the fullest degree possible the instruments developed during the past year. To this end a total of thirteen balloon flights have been attempted since May 1. Of these thirteen attempts, six failed because of problems associated with the launch operation or with the balloon itself; seven attempts were completely successful. In all of these launches or launch attempts the experiments were recovered with only minor damage.

The experimental objectives of the "balloon x-ray" program can be summarized briefly as follows: 1) to complete the general sky survey in both the northern and southern hemispheres; 2) to supplement the results of the present sky survey using instruments of higher sensitivity and better spectral resolution; 3) to determine the energy spectra of selected sources with greater precision and resolution; 4) to measure the size of selected sources with high precision; and 5) to search for time variations in the flux of x-rays from known sources. A description of specific experiments follows.

1. During the past year a general survey of the northern sky was carried out using a 400 cm^2 NaI telescope. Energy spectra in the range 20 to 70 keV were obtained for Tau X-1 and Cyg X-1. In addition it was found that Sco X-1 was markedly less bright in this energy region than reported by Peterson during a previous observation.

   The telescope was shipped to Australia in September 1967 to carry out a similar survey of the southern sky. Two successful flights were obtained. (W. Lewin, G. Clark, W. Smith)

2. Two experiments which use large proportional counters to obtain increased sensitivity and energy resolution have been constructed and flown. Data from both experiments are being analyzed at the present time. One of these instruments is a large area device with moderate angular resolution. It is being used as a sky survey instrument and to "scan" selected sources. (I. Glass, G. Clark)

3. The second instrument has an angular resolution of roughly 4° and contains an active orientation system so that it can be pointed at an object of particular interest. In the first flight the detector looked at the Virgo region for about two hours and at the Cygnus region for about one-half hour. (R. Sullivan, G. Clark)

4. A balloon-borne instrument for measuring the angular diameter and location of high energy x-ray sources is being constructed. It employs star photography and an Oda modulation collimator. The required pointing accuracy is achieved with a gyro-stabilized balloon gondola. (F. Floyd, H. Schnopper)

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5. A high rate of background counts in comparison to the rate of counts due to cosmic sources is a major problem encountered with the conventional scintillation and gas counters that are used in the investigation of the spectra of celestial x-ray sources. Since Compton interactions of high energy photons in the detector are thought to contribute a substantial portion of this background at balloon and satellite altitudes, we have devised an x-ray detector which has not only a high detection efficiency and good energy resolution for x-rays in the 15-80 keV range, but also a low detection efficiency for Compton electrons in the same energy range. This detector is a multi-anode krypton or xenon-filled fluorescence-coincidence protportional counter. A characteristic signature for the detection of a photon with energy above and near to the K-edge of the detector gas (krypton: 14 keV; xenon: 35 keV) can be obtained in the form of the detection of the coincident occurrence of the primary K-photoelectron ejection event and the subsequent interaction of the fluorescent K x-ray of the detector gas. This signature is not easily forged by Compton electrons, which result from the interactions of high energy photons in the detector, and which in general are not detected as even simple coincidences.

A small prototype of the detector has been built in order to study the characteristics of the multi-electrode detection system. This prototype has confirmed the validity of the most fundamental feature of the design. It has demonstrated that a "cell" (2.5 cm x 1.25 cm) defined by eight cathodes (ground wires) surrounding a central anode behaves exactly like and has resolution (10 percent FWHM at 24 keV) comparable to a conventional proportional counter having a completely solid cathode structure. In other words, it has been verified that a large detector may be divided into many small independent wall-less counters by using relatively few cathode wires. The detection of x-rays as coincident events occurring in two different cells or groups of cells is thus completely feasible. Such coincident detection has, in fact, been demonstrated using the prototype.

A large version of the detector is being manufactured and will be incorporated in a balloon gondola now under construction. The instrument will be used in a survey directed at the detection and spectrum measurement of high energy x-ray sources. (J. Stein, W. Lewin)

6. In measuring 20-100 keV x-ray fluxes from cosmic x-ray sources, large changes have been found in these fluxes with time. The high energy x-ray source in Cygnus was definitely established to be Cygnus XR-1 and not Cygnus X-3 or Cygnus A. The equipment developed for these studies includes a precise pointing control for the balloon gondola which makes possible very sensitive measurements of several x-ray sources during a single flight. It is being applied to a continuation of the time variation studies and to measurements with higher energy resolution than heretofore achieved. The high resolution detectors are a single xenon proportional counter and a lithium-drifted germanium crystal. (H. Tananbaum, E. Womack, J. Overbeck)

7. Preliminary results show that anthracene, due to its anisotropic scintillation properties, is an efficient detector of x-ray polarization at 25 keV. Its efficiency is

approximately the same as that of Compton scattering from low Z elements such as beryllium or lithium. Both methods seem to be impractical for balloon measurements at present. Anthracene should be investigated at lower energies than 25 keV and new higher Z scintillators should be investigated for anisotropy because they would be practical for the x-ray energies accessible to balloons. (J. Overbeck, E. Miller, Jr.)

B. Satellite Experiments

1. A prototype high resolution spectrometer is being developed for satellite use. The instrument uses a paraboloid-hyperboloid reflection concentrator to produce a high quality image of the source which then acts as the source for a focussing x-ray spectrometer. The chosen design maintains a high signal-to-noise ratio by analyzing a concentrated beam with small detectors. (H. Schnopper, G. Clark, R. Thompson, S. Watt)

2. An x-ray experiment is being constructed for the OSO-H satellite scheduled for launch in 1970. The experiment is designed to provide information concerning the position of the sources, their energy spectra in the range 1 to 60 keV, and the variation of the source intensities with time. (G. Clark, H. Bradt, W. Lewin, R. Rasche, H. Schnopper, J. Stein, R. Thompson, S. Watt)

C. Rocket Experiments

1. During the March 1966 flight (performed in collaboration with AS and E) data were obtained on Sco X-1 and on Tau X-1. Results for Sco X-1 have been reported previously. For Tau X-1 the x-ray source region is centered within 15" of the optical source region. In contrast to the earlier lunar occultation measurements of Tau X-1 by the NRL group, the present experiment gives position information along two scan directions instead of one. The data also show that the source is finite and is about 100" in diameter.

2. A second rocket experiment was flown in July 1967. The data are not yet completely analyzed but the following conclusions can be made: (1) There is a definite source close to M-87. It is very likely that M-87 is itself the source. (2) At the present levels of sensitivity the quasar 3C273 is not a source; and (3) the positions of about five x-ray sources in Sagittarius have been obtained, each with a precision of about 400 square arc minutes.

Thin window counters flown on this flight operated properly, and it will be possible to obtain spectral information in the 8-12 Å region. This should resolve the question of whether or not there is a cut-off in this region. (H. Bradt, G. Clark, G. Garmire, W. Mayer, S. Naranan, S. Rappaport, G. Spada, B. Sreekantan)

II. Gamma-Ray Astronomy

The OSO-3 high energy gamma-ray experiment is working well. At this time it appears that sufficient data have been received from the satellite to determine the origin of those gamma rays which are observed to come from the sky. A detailed analysis of the data is in progress and will be completed in about six months. (W. Kraushaar, G. Clark, G. Garmire)

III. Interplanetary Plasma

A. Satellite and Probe Instrumentation

During this reporting period experiments were successfully launched on Explorer 35 (lunar orbit) and on Mariner V (Venus mission). Both experiments are working well and preliminary results from each show that the solar wind interacts with these bodies in a very different manner than with the earth. Preliminary results have been reported for the moon and are in preparation for the Venus encounter.

The IMP-H and -J design effort continues but at a reduced level because of delays in the overall program. (J. Binsack, H. Bridge, J. Davis, T. Dawson, A. Lazarus and E. Lyon (LNS); R. Butler, G. Knapp and S. Viret (CSR))

B. Analysis of Data from Satellite Experiments

Work continues on the analysis of data from plasma experiments carried on OGO-1, OGO-3, Mariner IV, Pioneer 6, Pioneer 7, Mariner V, Explorer 33 and Explorer 35. A summary of this work for the individual experiments follows.

1. Data from the electron experiments carried on OGO-1 and OGO-3 have shown that intense fluxes of low energy electrons within the magnetosphere occur in a well defined spatial region now called the "plasma sheet". Recent work has concentrated on determining the boundaries of this region and in correlating variations in boundary position with the occurrence of magnetic bays. (V. Vasyliunas)

2. The motions of the earth's bow shock during two magnetic storms were observed by OGO-1. At the same time solar wind data are available from IMP-2 or IMP-1. The observed motion was compared with that predicted from a simple pressure balance model, and reasonably good quantitative agreement was found. To a good approximation large scale motions of the bow shock represent a simple contraction or expansion of the entire magnetosphere-bow shock system in response to changes in the dynamic pressure of the solar wind. (J. Binsack, V. Vasyliunas)

3. Experimental data from the deep space probes Pioneer 6 and Pioneer 7 have been analyzed to give plasma parameters as a function of time during the lifetimes of these two satellites. Using these data and the data from other space probes, we are attempting to study the characteristics of plasma flow from the sun as a function of radial distance

and azimuthal angle. This kind of comparison is particularly important and interesting during and after a large solar flare.

In addition to the large amount of data they obtained in the interplanetary region, both Pioneer 6 and Pioneer 7 provided very interesting results during the short times they were near the earth. Pioneer 6 passed through the magnetosheath at about 6:00 p.m. local time during a quiet period. The velocity distribution of the protons in this region does not fit a Maxwellian, nor is it fitted by our standard "kappa" distribution. Work continues on this problem.

Pioneer 7 passed through the "tail" region of the magnetosphere and measured there the density and energy spectrum of electrons in and near the plasma sheet. These results have been combined with magnetic field data obtained by other experimenters on Pioneer 7 in an attempt to understand physical conditions in the tail region of the magnetosphere. (A. Lazarus, G. Siscoe, H. Howe)

4. The Explorer 33 satellite is the most eccentric earth orbiter launched to date (apogee ~ 70 earth radii). This orbit allows a more extensive mapping of the magnetosphere and shock boundaries than was previously possible. Also it allows frequent sampling of the undisturbed interplanetary plasma. Plasma velocities in the range 300 to 700 km/sec and densities in the range 2 to 95/cc have been observed. (E. Lyon, J. Binsack, C. G. Wang)

5. The instrumentation carried on Explorer 35 is nearly identical to that on Explorer 33. The satellite, however, was put in orbit about the moon. Early results indicate that the plasma interaction with the moon is very different from that with the geomagnetic field; the moon appears to behave as a diamagnetic sphere. A detailed study is in progress. (E. Lyon)

6. The Mariner V spacecraft flew past Venus on October 19, 1967. The plasma probe aboard the spacecraft operated well throughout the flight. During encounter, data from the plasma probe and from the magnetometer (provided by other experimenters) clearly revealed a shock-like region of disturbed solar wind plasma in the vicinity of the planet. The region of interaction is much smaller than that which surrounds the earth but much larger than that seen around the moon. From the size of the interaction region one can conclude that, if Venus has an intrinsic magnetic dipole field, its strength is less than one three-hundredth that of the earth. (A. Lazarus, H. Bridge, T. Dawson (LNS); C. Snyder (JPL))

C. Theoretical Studies

1. Properties of an Anisotropic Plasma

Among various questions concerning the behavior of the interplanetary plasma (the "solar wind") the following two have been under theoretical investigations during the last six months:

a. The issue of the experimentally established anisotropy of the plasma pressure tensors. The observed ratios of pressures, referring respectively to particle motions along and at right angles to the magnetic field lines, are in strong disagreement with those predicted by the "double adiabatic hypothesis" of Low, Chew, and Goldberger. A rather effective interaction between particles and fluctuating electromagnetic field (finite amplitude waves, etc.) must be taking place. Some statistical models of this latter phenomenon are being studied.

b. The issue of the collisionless shocks in anisotropic plasma. The presence of anisotropy warrants the generalization of the classical Rankine-Hugoniot relations across the surfaces of discontinuity in the solar wind. Conservation laws for mass, momentum and energy, and Maxwell equations do not suffice to establish unique relations between physical quantities in the pre- and post-shock states. The case of the "missing equation" is being investigated further.
(S. Olbert and J. J. K. Chao)

2. Solar Wind Fluctuations

Solar wind fluctuations (or turbulence) are being studied theoretically in preparation for an analysis of the available data. Most of this work is being done by a graduate student, Bruce Goldstein, who is interested in turning it into a thesis. At this point he has a program for generating power spectra which is being checked out, and he is working on one for generating cross spectra. We intend to analyze mostly magnetosheath data (from Mariner 4, and Pioneer 6 and 7) since this region is most likely to be highly turbulent. The magnetic field data will also be required for this analysis. A theoretical paper on the radial dependence of solar wind fluctuations is now nearly completed.
(G. Siscoe)

3. Geophysical Phenomena

The correlation between ground magnetograms and the dynamical solar wind pressure (ρV^2) is being studied using the Pioneer 6 data. Theoretical predictions exist for the purpose of comparison and interpretation. The preliminary results look very interesting, and possibly suggest a need for some revisions of the theoretical models. This work is being done in collaboration with Vittorio Formissano.

Studies of auroras are being conducted both theoretically and, shortly, experimentally in the way of laboratory simulations. The theoretical studies suggest a reason why auroras tend to form into narrow filamentary arcs, and the idea will be tested using an electrical analog in the laboratory. The experiment is being done by David Brookfield as a senior thesis. (G. Siscoe)

IV. BASJE Air Shower Program

A. BASJE Cerenkov Light Experiment

During October and November of 1966, an array of four Cerenkov detectors was operated during 53 clear moonless nights on Mt. Chacaltaya in Bolivia (altitude 17,200 feet). Cerenkov Light (CL) signals were obtained from about 1100 EAS with this array. Several thousand additional EAS were recorded during other periods with portions of this array.

The data yielded results concerning: 1) the lateral distribution of individual EAS out to 300 m; 2) the average lateral distribution of EAS as a function of shower size; and 3) fluctuations in the CL density at fixed shower size and radius from the core. In summary, these results are the following:

1. The shape of the lateral distributions of individual EAS exhibited wide fluctuations which must arise from fluctuations in the shower development.

2. The yield of CL normalized to shower size is greater for small EAS than for larger EAS. This indicates that the parameter, N_{CL}/N_e, is a measure of the degree of shower development above the observation level: i.e., a measure of the "age" of the shower.

3. The CL yield at fixed shower size and radius fluctuates much more than that expected from measurement fluctuations alone.

These results indicate that the initial objective of the experiment can be fulfilled, namely the classification of EAS into roughly defined groups according to the atomic number of the primary particles. For instance, EAS with Fe primaries differ from those with proton primaries in that they are expected to have a more advanced "age" and also to exhibit significantly smaller fluctuations in the quantity N_{CL}/N_e.

This analysis was completed at MIT in the spring of 1967. During the same period, several modifications to the equipment were designed and fabricated at MIT. Mr. Krieger's dissertation was based upon this work, and he earned the Ph.D. degree in July 1967. He returned to Bolivia in June with two undergraduate physics majors, Mr. G. Minagawa and Mr. T. Jach, to install the entire thirteen-detector array. The entire array was operational at the end of August. Data are being obtained from this array at the present time. (H. Bradt, A. Krieger)

B. Analysis of BASJE Nuclear Burst Data

The characteristics of the nuclear core of EAS are closely related to the type of primary particles of the EAS and to the character of the high energy nuclear interactions which take place in the core. In an attempt to understand this relationship, we have carried out a three-dimensional Monte Carlo simulation of EAS for several models of nuclear interactions and types of primaries. A paper describing the results of this calculation was submitted to the Physical Review in August 1967. Energy and spatial distributions of nucleons, pions, and nuons at the atmospheric depths 530 and 970 g/cm^2 are presented.

We are now using the simulated EAS to generate simulated data in the BASJE 60 m^2 shielded detectors. Energy calibrations of the detectors were obtained from an independent Monte Carlo calculation which we have recently carried out.

The artificial data for EAS with Fe primaries and those for EAS with proton primaries will be compared to real BASJE data in an attempt to obtain information concerning the primary composition at primary energies of 10^{14}-10^{16} eV. The dissertation of Mr. Rappaport will be based upon this work. (H. Bradt, S. Rappaport)

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J. Binsack: "Observations of the Interplanetary Plasma after the Solar Flare of July 7, 1966", 10th COSPAR Meeting, London, July 1967.

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H. V. Bradt: "Observations of Atmospheric Cerenkov Light Associated with EAS at 5200 m Altitude", 10th International Cosmic Ray Conference, Calgary, June 1967.

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N68-36575

ACCELERATOR PHYSICS COLLABORATION

I. Scope

The program of the APC consists of four main parts:

A. Completion of Charge Exchange Reactions from One to Four BeV/c:

The exposure in our high-Z spark chamber was taken three years ago. Although serious difficulties occurred in the classifications of the events, they have now been clarified, and the analysis of the experiment should be successfully completed in the near future.

B. PEPR

The commercial components of a three-view PEPR have been ordered and they should soon be delivered. Twenty thousand $\bar{p}p$ interactions have been measured using both PEPR and hand measuring techniques.

C. MIT 500 Liter Bubble Chamber

Ground has been broken for the MIT 500 liter bubble chamber facility at the Argonne National Laboratory. This chamber will be first used in a multi-BeV pion study. We have received 30,000 π^+ pictures taken with the MURA 30" chamber as a start on this study. We are scheduled for an additional 70,000 pictures.

D. Counter Work at ANL

One counter experiment at ANL has been completed. Analysis of this is in progress.

II. Results

A. Spark Chamber

Our spark chambers do not measure the energy of gamma rays. Hence, an event that contains more than one π^0 is unconstrained. But the total neutral cross section at these energies is dominated by multi-π^0 production, and in addition, our chambers have certain inefficiencies. Therefore, the classification of events is difficult.

We have, however, developed a model for these multi-π^0 events that fits all of our experimental data. Hence, it now seems possible that we will be able to analyze this experiment properly.

This group is not committed to any BNL spark chamber experiment at this time.

B. PEPR

The prototype PEPR has measured approximately 1,000 tracks to determine the quality and accuracy of its measuring mode. These measurements were compared with hand measurements of the same tracks. The precision of PEPR is measured to be a factor of two better than manual machines.

All the measurements have been completed on the $\bar{p}p$ experiment. Some 20,000 events have been measured with PEPR, manual machines.

The first Astrodata Model of a three-view PEPR has been delivered to MIT. This is being checked out by a group from Nijmegen University (Holland) and MIT personnel, and will be sent to Nijmegen when it is accepted. The MIT machine should be delivered early in 1968. Preliminary tests of the Astrodata machine indicate excellent performance.

The prototype PEPR has been converted to handle the MURA 30-inch film. To date it has measured 1,000 events of the π^++p experiment and the results of these measurements are very promising.

C. MIT 500 Liter Bubble Chamber

Construction of the MIT 500 liter bubble chamber facility at ANL has begun. All foundations are installed and the crane rails are in place. The "tin tent" (Butler style prefab building) should be erected in the next month. Complete occupancy is scheuled for April, 1968, but beneficial occupancy may occur before then.

The chamber is presently being assembled in the new extension of the experimental hall; and we will start an intensive test at liquid nitrogen temperatures in 1968.

The preliminary experiments done in this chamber will be a multi-BeV pion study. As part of this study, we requested 100,000 π^+ pictures at 3.9 BeV/c in the MURA 30-inch chamber. We have received 30,000 of these, and expect to receive the remainder shortly.

At present, two IPD tables, one hand-measuring machine and PEPR have been converted to the π^+ film. We expect to go into production in the next month. Our initial rate should be of the order of 1,000 events/week.

D. Counter Work at ANL

An experiment was performed to study the production mechanism in the forward direction of high energy π+ mesons produced by π^- mesons. Targets of lead, copper, carbon, beryllium, and hydrogen (polyethylene-carbon differences) were used. The possible mechanisms for this production are:

$$\pi^- + N(A,Z) \rightarrow \pi^+ + N(A, Z-2) \quad (1)$$

$$\pi^- + N(A, Z) \rightarrow \pi^+ + \pi^- + N(A, Z-1) \quad (2)$$

$$\pi^- + N(A, Z) \rightarrow N(A, Z-1) + \rho^0 \quad (3)$$
$$\qquad \llcorner\!\!\rightarrow \pi^+ + \pi^-$$

$$\pi^- + N(A, Z) \rightarrow N(A, Z-1) + f_0 \quad (4)$$
$$\qquad \llcorner\!\!\rightarrow \pi^+ + \pi^-$$

Accelerator Physics Collaboration

Mechanism (1) is of special interest as it presumes the existence of di-protons in the nucleus. Process (2) is straight single pion production, and is not expected to contribute a large contribution of high energy π^+ in the forward direction. The contributions due to processes (3) and (4) depend on the initial production cross section, state of polarization of the produced particles and the reabsorption in the nucleus. Measurements were made of the energy dependence of the production of high momentum π^+ in the forward direction on all targets. A preliminary examination of the data concludes that Process (1) (i.e., di-protons in the nucleus) is not the major production mechanism. The major production mechanism seems to be Process (4).

Preliminary indications are that very pure (approximately 90%) π^+ beams can be created with moderate π^- beam intensities. These beams are more than adequate for bubble chamber use and have the advantage of not needing separators.

No LNS funds were used for this experiment. The only LNS contribution to this experiment (although not negligible) was computer time and a few week's time of Vera Kistiakowsky (who is the major MIT contributor to this work).

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N68-36576

LINEAR ACCELERATOR GROUP

I. NBS Collaboration: Electron Scattering

Design of the 180° electron scattering magnet to be used with the NBS electron linac and electron spectrometer has been completed. The magnet is being constructed by Alpha, Inc., of California, and should be available for testing in the spring of 1968. Work is now progressing on related equipment, in particular: target chambers that allow for the recovery of and circulation of liquids; and the vacuum chamber for the 180° magnet system containing a sliding vacuum seal to allow continuous and rapid angle changes. We have also embarked on a program of calculations of line shapes for electron scattering that include among other effects radiation and landau straggling. Experimentation using an O^{16} target and scattering at angles smaller than 160° is scheduled to begin about March 1968.

II. Status of 400 MeV Linac Project

A. General

The project is divided into ten major tasks, four of which (Buildings and Facilities, Bennett Construction Co.; R. F. Transmitters, Energy Systems, Inc.; Accelerating Waveguide, Varian, and R.F. Power Feed Waveguide,SLAC) are basically managed by outside major contractors and represent 80 percent of the costs of the project. Design activity on these four tasks has been completed, all contracts let, and construction is proceeding satisfactorily.

The remaining six tasks, Injection System, Beam Handling System, Vacuum, Cooling, Controls and Installation are those which are being managed by LNS. Of these tasks the designs for the vacuum system and the cooling system are complete and parts have been ordered. Definitive design on all remaining systems is scheduled for completion by the end of FY 68.

B. Progress to Date

With regard to the work being done on the four major contracts, the building contractor has completed about 8% of the job and is on schedule. The rf transmitters are about 20% complete with no serious problems apparent at the time. The final design of the accelerating waveguide including iris and spacer dimensions has been completed and transmitted to Varian and a complete Acceptance Testing Procedure has been worked out. About 25% of the hardware to be fabricated by SLAC has been completed.

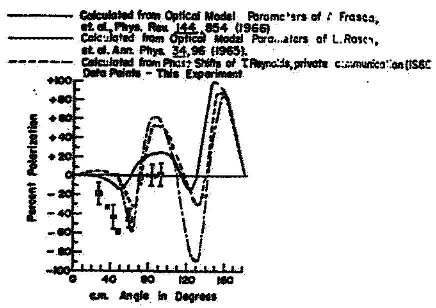
Regarding the LNS in-house effort, arrangements regarding the transfer of the spare magnets, obtained from the Princeton-Pennsylvania Accelerator, representing about 25% of the effort on the beam handling system have been completed and arrangements are being made for their shipment and completion. Conceptual design on the remaining beam handling equipment is virtually complete. Conceptual design on the injector system is expected to be completed by the summer. Many parts for the vacuum, cooling and control systems have been ordered and all parts for these systems will be ordered by the fall of 1968. Also, all of the interface problems regarding the installation of the waveguide and rf transmitters with the building have been resolved. Remaining installation problems are in the conceptual design stage.

C. Schedule

Prototype tests on the first transmitter (including the high power klystron) and on the first waveguide section are scheduled for the summer of 1968. Installation of transmitters and waveguide is scheduled to start in January of 1969 with beam handling and research equipment starting in March of 1969. Accelerator trials should begin in late 1969 and trials with research equipment by the summer of 1970. The research program should get started in the fall of 1970.

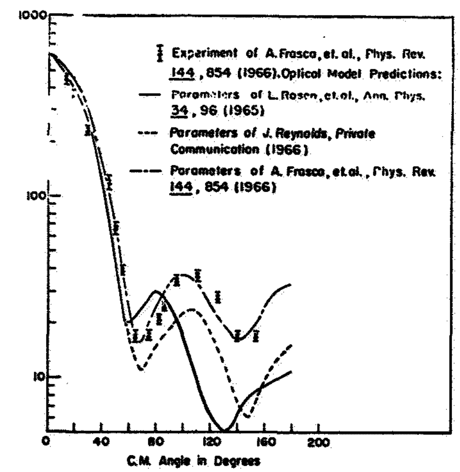
III. Polarization of Scattered Neutrons

The determination of the angular distribution of the polarization of elastically and inelastically scattered fast neutrons is continuing (see MIT Progress Report, October 1, 1966). The polarization angular distributions for 14.7 MeV neutrons elastically and inelastically scattered by carbon-12 has been measured at eight angles. Fig. 3.1 shows the results for the elastic events. The curves are calculations of the polarization based on three optical models. The elastic differential scattering cross section can be fitted reasonably well using these models (see Fig. 3.2) but, as shown in Fig. 3.1, the models predict polarizations which are not in agreement with the data.



POLARIZATION ANGULAR DISTRIBUTION FOR THE $C^{12}(n,n)C^{12}$ REACTION FOR 14.7 MeV INCIDENT NEUTRONS

Fig. 3.1



CARBON 12 DIFFERENTIAL ELASTIC SCATTERING CROSS-SECTION 14 MeV NEUTRONS

Fig. 3.2

Fig. 3.3 shows the polarization angular distribution for those neutrons that have left the carbon-12 nucleus in the first excited state, the 2^+ state at 4.43 MeV.

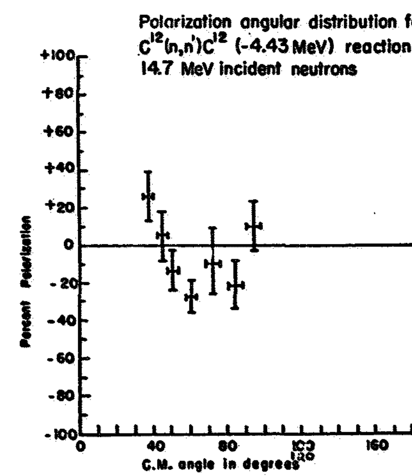


Fig. 3.3

Four liquid scintillation counters have been added to the polarimeter making a total of eight counters to detect the left-right asymmetry in a second scattering of the neutrons by the high pressure helium xenon scintillation counter.

Extensive maintenance was done on the neutron generator and it is now capable of producing a 1 ma beam of deuterons. A gate valve was installed to permit easy changing of targets, and a multiple target assembly was installed which allows quick replacement of up to five tritiated titanium targets.

Measurements are in progress to extend the carbon-12 angular distribution and a calcium-40 target has been fabricated in order to obtain polarization distributions for this element. (M. Zombeck)

III. High Energy Photoeffect Studies

Measurements have been made of the distribution in energy and angle of the high energy protons emitted in the photodisintegration of Li^6, with some limited studies also of Li^7 and C^{12}. The experiments were performed at the University of Saskatchewan Accelerator Laboratory using a 100 MeV bremsstrahlung beam. Protons of energies between 40 and 95 MeV were detected with about 4% resolution, at eight angles from 45° to 126° by an array of plastic scintillation counter telescopes. Some of the motivations for this work, some experimental details, and some of the data have been discussed in our previous progress report.

The principal results of the experiment are shown in Figs. 3.4 and 3.5: the proton spectra at eight angles observed in the $Li^6(\gamma, p)$ reaction. The differential cross section scale, which is accurate to about ± 20%, was established by comparing similar measurements on C^{12} with the results of a previous experiment.[1] The vertical error bars are statistical; the several horizontal error bars in each spectrum represent the uncertainty in the energy calibration at one angle relative to another.

The curves are the prediction of a phenomenological quasi-deuteron model, in which the cross section for photoproton emission is written[2]

$$\frac{d^2\sigma}{dE_p d\Omega_p} = C' \frac{LNZ}{A} \int d^3P \; F(P) \left(\frac{d\sigma}{d\Omega^*}\right) \left(\frac{d\gamma}{d\omega}\right) J \qquad (1)$$

The constant C' is included to normalize the total quasi-deuteron cross section to (LNS/A) times the free deuteron photodisintegration cross section: NZ is the number of neutron-proton pairs in the nucleus of mass number A, and L gives a measure of the increase in the probability that the members of a pair be within a suitable interaction distance in the nucleus, compared with that in

1. C. Whitehead, W.R. McMurray, M.J. Aitken, N. Middlemas, and C.H. Collie, Phys. Rev. 110, 941 (1958).
2. J. L. Matthews, Ph.D. Thesis, Dept. of Physics, MIT (1967).

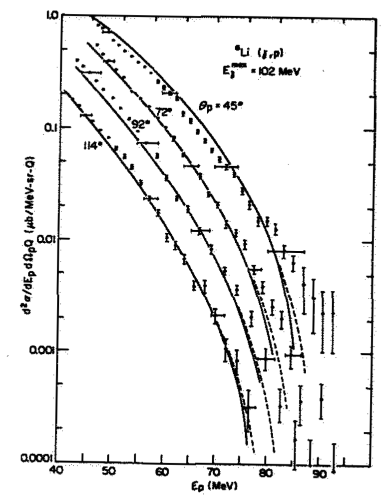


Fig. 3.4

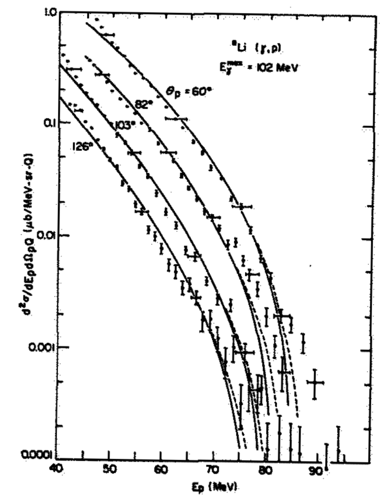


Fig. 3.5

the free deuteron. F(P) is the neutron-proton pair momentum distribution, which we take to be of the Gaussian form

$$F(P) = (2\pi\alpha^2)^{-3/2} \exp(-P^2/2\alpha^2) \qquad (2)$$

$\left(\frac{d\sigma}{d\Omega}\right)_d$ is the cross section for the photodisintegration of the free deuteron, and $\left(\frac{df}{d\omega}\right)$ is the incident photon (bremsstrahlung) spectrum. J represents the product of the Jacobians which arise in the coordinate transformations necessary in the calculation. The integration is carried out essentially over all $\vec{P}$-space, with the restriction that each event included must be physically allowable. That is, in each case in the integration, the photon energy must be at least E_{recoil} + 4.66 MeV (for Li^6) greater than the laboratory proton energy.

The shape of the cross section derived from Eq. (1) is determined mainly by the parameter α in Eq. (2) and the value found to produce the best fit to the data shown in Figs. 3.4 and 3.5 was

$$\alpha = 80 \pm 15 \text{ MeV/c}.$$

The parameter L was determined by comparing the scale of the measurement (corrected for the absorption of the outgoing protons by the residual nucleus) with that of the prediction, with the result

$$L = 4.5 \pm 1.0$$

The dashed curves at the high energy ends of the spectra result from folding into the calculation the experimental resolution: the spread in proton energy due to the Li^6 target thickness, and the ~4 % energy resolution of the proton detector. The calculation is seen to reproduce the data satisfactorily over the entire range of the measurement.

We have also investigated the prediction of a single-particle model for the photoeffect, as previous work[1,2] has suggested that some features of the shell model might be important at the highest proton energies. To achieve greater experimental sensitivity to these effects, we obtained proton energy spectra from a simulated monochromatic photon spectrum by forming a properly normalized difference between data taken with 102- and 95-MeV bremsstrahlung beams. A typical result is shown in Fig. 3.6. Curves A and B represent the prediction of a Born approximation calculation on the basis of the single-particle model for the photoeffect in Li^6.[3] Protons are assumed to be ejected from the s- and p-states, with the separation energies and state widths taken from the (p, 2p) experiments.[4] The experimental resolution, in this case dominated by the ~8 MeV width of the photon spectrum, has been folded into the calculated cross sections, for square well initial state wave functions (Curve A) and harmonic oscillator wave functions (Curve B). The predictions are seen to be at least one order of magnitude below the

1. C. Whitehead, W. R. McMurray, M. J. Aitken, N. Middlemas, and C. H. Collie, op. cit.
2. G. M. Shklyarevskii, Soviet Phys. - JETP 9, 1057 (1959); S. Fujii, Prog. Theor. Phys. 29, 374 (1963).
3. J. L. Matthews, Ph.D. Thesis, Dept. Physics, MIT (1967).
4. H. Tyren, S. Kullander, O. Sundberg, R. Ramachandran, P. Isacsson, and T. Berggren, Nucl. Phys. 79, 321 (1966).

measurement. We may conclude that simple shell model wave functions do not provide sufficient amplitudes in this high momentum region ($k_p \approx 400$ MeV/c) to account for the observed (γ, p) cross section.

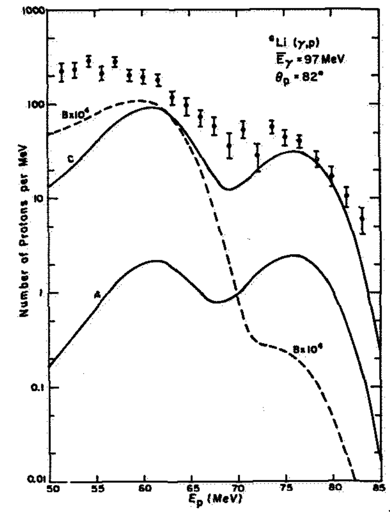


Fig. 3.6

Curve C is the same calculation with an empirical momentum distribution derived from the experiments of Selove[1] on the (p, d) reaction. There, in the impulse approximation picture, a neutron is picked up from approximately the same region of momentum space as in the photoeffect. This prediction, perhaps fortuitously, gives the correct order of magnitude for most of the (γ, p) spectrum. However, neither of the curves reproduces accurately the shape of the spectrum below about 65 MeV. Or rather, the data do not show the "s-state peak" predicted by the simple single-particle model. The validity of a detailed comparison of these results with the model is thus questionable at all but perhaps the highest energies (the p-state region).

In Fig. 3.7 we show the angular distribution of these highest energy ("p-state") protons. The experimental resolution has been unfolded from the data of Fig. 3.6 and similar spectra at the other angles. The solid curve represents the prediction of the single-particle model using the momentum distribution derived from the (p, d) experiments; with this distribution given by Selove[1] as an absolute density in momentum space, there are no adjustable parameters in this calculation. The prediction is seen to be in good agreement with the (γ, p) measurement. For comparison, the dashed curve in Fig. 3.7 is the angular distribution obtained from the calculation with square-well wave functions. (J. L. Matthews)

1. W. Selove, Phys. Rev. 101, 231 (1956).

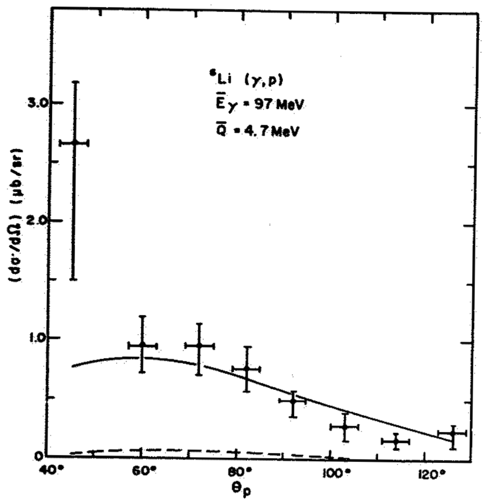


Fig. 3.7

V. $(\alpha, 2n)$ and $(\alpha, 3n)$ Reactions on Rare Earth Nuclei

Work has continued on the study of the intensity distributions of rotational gamma rays in even-even deformed nuclei arising from the $(\alpha, 2n)$ and $(\alpha, 3n)$ reactions. In previous work[1] there were indications that the intensity distributions might be more strongly influenced by the low-lying states just above the energy gap than by the statistical emission of neutrons and photons. In order to check this hypothesis a number of pairs of separated rare-earth isotopes have been ordered and made into targets. These were chosen so that the $(\alpha, 2n)$ and $(\alpha, 3n)$ reactions lead to the same final nucleus. However, at the energy of the MIT cyclotron the $(\alpha, 3n)$ reactions only populate the low-lying states of the residual nucleus, while the $(\alpha, 2n)$ can populate states up to the neutron binding energy. A preliminary run has been made on $Er^{166}(\alpha, 2n)\,Yb^{168}$ and $Er^{162}(\alpha, 3n)Yb^{168}$. The intensity distributions of the rotational transitions appear to be essentially identical, lending support to the hypothesis that they are strongly influenced by the low-lying levels. A number of other pairs will be studied shortly. (W. J. Kossler, C. F. Williamson (MIT); C. Kavaloski (Lowell Tech))

1. C. F. Williamson, B. J. Shepherd, I. Halpern, and S. M. Ferguson, to be published in Phys. Rev.

VI. Summer Study on Intermediate Energy Physics with Electron Linacs

During July 5 - August 18 we convened a group of approximately 40 physicists. Among these were people from the local physics community interested in research on the new 400 MeV accelerator; about 13 people from Saclay, France, where a similar accelerator is being constructed, and recognized experts, both theoreticians and experimentalists in the fields of electron scattering pion physics, muon physics, photoreaction physics, etc. Daily discussions were held on new physics made possible by the high intensity, high duty ratio and secondary beams of photons, and mesons. Among the many things to emerge was the possibility of generating beams for stopped μ-meson experiments (such as μ-mesic atom studies) with intensities far greater than now exist. A proceedings of the discussions is in preparation. (W. Bertozzi)

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F. A. Hanser, W. Bertozzi, S. B. Kowalski, C. P. Sargent, W. E. Turchinetz, R. Fullwood, and J. Russell, "Angular Distribution of the Polarization of Photoneutrons from the Giant Resonance of O^{16} and C^{12}", Bull. Am. Phys. Soc. 12, No. 4, 516 (April 1967).

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N68-36577

HIGH ENERGY ACCELERATOR PHYSICS GROUP

I. Researches of the L. S. Osborne, D. Luckey, et al., Group

CEA Experiments

In the past year we have been analyzing the data taken during the spring and summer of 1966. We analyzed and published data on π^0 photoproduction from 2 to 6 GeV. Taken together with lower energy data measured at DESY this seemed to show agreement with an ω^0 exchange model for π^0 photoproduction. In combination with a group from Southeastern Massachusetts Technological Institute we measured and published data on the relative cross sections of π^- and π^+ photoproduction from neutrons and protons respectively. The fact that the π^-/π^+ cross section ratio is about 0.4 indicates that the mechanism for production cannot be one simple particle exchange. We completed and analyzed a large angle e^-e^+ pair photoproduction and obtained a result in agreement with quantum electrodynamics. In addition, we carried out an experiment looking for leptonic quarks which led to a lower limit for the mass of such objects (if they exist) of 900 MeV.

An experiment to study π^0 and η^0 photoproduction at forward angles by detection of their 2γ modes of decay is set up and taking data at the CEA. The lead glass hodoscope has been split into two arrays of 4 x 6. At some angles Moby Dick is used in coincidence.

The Moby Dick spectrometer has been outfitted with wire spark chambers and we are very pleased with their initial performance.

A polarized beam facility is being set up using a diamond radiator. A pair spectrometer is available for analysis of the beam. We shall study photomeson production. In particular we are interested in making further tests of the Regge pole model. A spectacular dip in differential cross section is expected for photons polarized perpendicularly to the production plane at $t = -0.6$ $(GeV/c)^2$. The important point is that a given exchanged particle produces π-mesons either only parallel or only perpendicular to E depending on the J-parity $[= \pm(-1)^J]$.

The Large-Angle Meson Photoproduction Group (LAMP) (R. Alvarez) completed taking data in May 1967 and has spark chamber photographs of 160,000 events. Preliminary rough scanning of a small fraction of these events indicates that approximately half should be unambiguously from single pion photoproduction: $\gamma + p \rightarrow \pi^+ + n$. We now have a working scanning program for the SPASS automatic scanning system and have scanned about 10% of our film with SPASS. We expect to have about half of our film scanned by the end of November. By that time we will also have completed most of the necessary computer programs to analyze the output of the scanning machine.

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II. Researches of the D. H. Frisch, *et al.*, Group

A. Brookhaven Experiments

1. $\pi^+\pi^0$ Mass Spectrum. This finally completed search at BNL-AGS for structure below the ρ-mass had allegedly favorable bombarding energy and the best statistics and resolution to date, and no resonances were found. (Results to appear in The Physical Review) The very large solid angle lead plate spark chamber array (no magnetic field) will be described in Review of Scientific Instruments. (P. Mockett)

2. Forward π-p Charge Exchange in the 2-6 GeV Region. The last of the many outputs of our forward-charge-exchange run at BNL-AGS has been submitted to The Physical Review. The resonances these data first indicated, and the Regge treatment they revivified, are now nothing new. (I. Mannelli, M. Wahlig)

3. MASCOT rogram. The analysis of experimental data on all-neutral final states containing strange particles produced by 8 GeV/c K^- and π^- has continued. These data were taken with the MASCOT large solid-angle, magnetic spark-chamber system in early 1966.

Work is nearing completion on K^--induced final states containing a single V-particle. Approximately 6000 events will be measured, with approximately 300 events expected to fit the charge-exchange reaction $K^- + p \rightarrow \bar{K}^0 + n$. Preliminary results from this analysis indicate a cross section of 71 ± 21 microbarns and an angular distribution consistent with results from other experiments. Most of the remaining non-charge exchange events result from non-peripheral $\bar{K}^0$ and Λ^0 production processes. These data are currently being studied for information on the nature of high momentum-transfer processes at high energy, in a manner similar to that of Ratner, *et al.*, (Phys. Rev. Letters **18**, 1218 (1967)).

Approximately 150 K^- induced events with two observed V-particles, from such reactions as $K^- + p \rightarrow K^0 + \bar{K}^0 + \Lambda^0$, will be available for study in the complete data sample. Scanning and measurement of these events is nearing completion.

A study of π^--induced double-V events was carried out, using one-third of the total data. The A_2^0 meson was observed through its decay into $K_1^0 + K_1^0$, and an estimate of the branching ratio

$$\frac{A_2^0 \rightarrow K\bar{K}}{A_2^0 \rightarrow \pi\rho} = 7 \pm 4\%$$

was made. Angular distributions and cross sections were in agreement with other published results. It was not felt worthwhile to continue analysis of the remaining two-thirds of this data because the quality of the results was expected to be low compared to other published data. (A. Buffington, C. Ward, C. Nelson, H. Emery, M. Shupe)

4. Dikaon Resonances. A test has been run on $\pi^- + W \rightarrow$ Miscellany $+ K_1^0 + K_1^0$ using nothing but track angle and location information. The rates were roughly as expected. The $K_1^0K_1^0$ data is now being digested to see whether the A_2 peak is pretty much unaffected by production from a complex nucleus. If so, we will take a high intensity run to search for the S^*, etc. (G. Smoot, D. Fox, G. Gulledge)

5. $\Delta S/\Delta Q$ Study. Our $K^0 \rightarrow \pi^\pm + e^\pm + \nu$ experiment to test $\Delta S/\Delta Q$ has long since been approved for running at BNL (Experiment No. 292). Design and construction of equipment for this experiment is virtually complete. We are now waiting our turn to move into the G10 separated beam, probably the world's most popular beam. (O. Fackler, L. Sompayrac, J. Martin)

B. CEA Experiments

1. CEA Tagged Photon Beam. The internally tagged beam is working and ready for use. A quartz filament ~2 microns in diameter is used as the machine target, and may be moved into the beam whenever the machine is operating. Only one experiment in its normal use has been affected adversely, and that not by much, and no other prime users with whom we have run have been able to measure any effect on their experiments. Intensity is presently limited, by electronics, to $\sim 10^5$ tagged gammas/clock sec, using a gate width of 10% of the acceleration cycle.

Analysis of the gamma beam with a simple pair spectrometer has put an upper limit of 3% (full width) on the tagging resolution at high energies, and a 1% check on energy calibration. The cause of an apparent tagging efficiency of only about 50% is not yet understood, but use of the beam is not affected by the presence of untagged gammas.

CEA is building a ceramic chamber to replace our present epoxy-sealed donut section. Their first design restricts the energy range available for tagging, but a cooperative development program is underway to develop a less restricting chamber. (S. Smith, S. Gray, E. Shibata, C. Strumski)

2. $\gamma + p \rightarrow \pi^0 + \pi^0 + p$. The first experiment for the internally tagged photon beam at CEA is to be $2\pi^0$ photoproduction. We hope to study the f^0 using CH_2 and carbon targets. Other $2\pi^0$ resonant structures may also appear. In particular, there is much interest in a possible T=0 state near 1650 MeV. The same apparatus may lend itself to a quick study of the z-dependence of resonant cross sections.

The gammas will be detected in a steel-plate spark chamber, and a foil chamber will be used to see those recoil protons which are energetic enough to leave the target. The instrumentation is complete and the experiment is now being installed at CEA. (S. Smith, S. Gray, E. Shibata, D. Newman)

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III. Researches of the L. Rosenson, et al., Group

A. Work on π^- Charge Exchange Now Being Completed within the A.P.C.

This work consists of two spark chamber experiments on π^- charge exchange from 0.5 to 1.1 BeV/c and from 1-4 BeV respectively. The analysis of this data has turned out to be quite complicated but is now being successfully completed. Angular distributions of $\pi^- + P \to \pi^0 + N$ and $\pi^- + P \to \eta^0 + N$ at eleven energies in the first experiment, and 23 energies in the second, are the most interesting results. This data is vital to an understanding of π nucleon interactions in this energy region, which is of course the region in which all the πN resonances have been found. Information on the classification of baryon resonant states is forthcoming. The onset of high energy diffraction like behavior of the scattering is evident and is under study with the hope of gaining some insight into, and possible discrimination between, various pictures of high energy scattering that have been advanced such as the Regge Pole model and the various liquid drop and optical models. (I. Pless, L. Ventura, B. Brabson, L. Rosenson, collaboration with Padova, Brown, Harvard, and Weizmann)

B. Work Now Being Completed and Performed Outside the A.P.C. Framework.

1. Spark Chamber study of the decay modes of the η^0 meson. The interest in this experiment is several-headed: 1) To compare ratios of partial widths with various model calculations and predictions, such as those of the quark model. 2) To pursue the consequences of various symmetry schemes and selection rules that have been proposed. For example, the A quantum number thesis of Bronzan and Low would lead one to expect $\frac{\eta \to \pi^0\gamma\gamma}{\eta \to \gamma\gamma} \sim 1$. The experimental situation is currently unclear with contradictory published results in the literature. The experimental run was completed in December of 1966, and the scanning and measuring are now substantially completed. Preliminary analysis is now underway (D. Barton, B. Nelson, L. Rosenson, collaboration with Padova and Brown).

2. Design construction and development of a spark chamber experiment to study strongly backward charge exchange processes in the 2-8 BeV/c region.

This work arises naturally out of our earlier charge exchange work and the interest in the recent data obtained by several groups on backward π^+-p elastic scattering data. The kinematic region involved is 150-180° in the c.m. This is the large t, small u, domain. The appearance of narrow backward peaks in the π^++p elastic scattering particularly, has led to the speculation that one is seeing baryon exchange processes. However, the backward scattering peaks can be due to resonant phenomena interfering with some background amplitude. Two things, at least, should emerge from this study: 1) a clarification of the dynamics of the large momentum transfer π-nucleon interaction. For this, the charge exchange data is vital to complete the picture gained from π^+-p elastic data. 2) The backward scattering processes seem to be an excellent way of searching for resonances and classifying them. In particular, because of the $(-1)^{\ell}$ factor on the backward partial wave amplitude, the parity of resonances can be deduced if the background amplitudes are reasonably behaved.

This experiment has been approved by the A.G.S. and we hope will be performed in winter, '68-69. A new 4π solid angle high-Z spark chamber system coupled to a high energy neutron detector is now being constructed for this experiment. (L. Rosenson, R. Thern, collaboration with Padova and Brown)

IV. Researches of the M. Deutsch, et al., Group

In addition to experiments carried out by members of this group with the support of the general service groups of this Laboratory and of CEA, the experimental program has included several collaborative undertakings with other research groups, both within LNS and at other institutions.

Scientifically, the research problems fall into two groups: Photon-nucleon interactions and K-meson decays.

A. Photon Experiments at CEA.

1. Proton Compton Effect.

The largest effort in the photon field has been directed towards the completion of the experiments on elastic scattering of gamma rays by protons, started in 1961. Cross section measurements at a fixed barycentric angle of 65° have now been obtained in the range 0.6 - 1.8 GeV of incident gamma ray energy, and their extension to about 2.5 GeV is close to completion.

In the energy range below about 1.2 GeV the scattering is apparently dominated by nucleon resonances. Comparison of the new results with our published data for 90° c.m. up to 0.8 GeV and with later Cornell and CIT data up to 1.2 GeV shows no strong variation of the cross section with angle. The relative contribution of the second and third resonance peaks compared with N*(1238) is larger than it is in pion interactions. Attempts at a phenomenological analysis (some of them published) have been made by several authors, but any strong statements must probably await inclusion of more complete photoproduction data.

We also hope to obtain some information on the polarization of recoil protons from elastic gamma ray scattering near 1.1 GeV in connection with the corresponding experiment for pi-zero photoproduction, described below. This may prove helpful in the phenomenological analysis.

At energies above about 1.5 GeV, photoproduction processes seem to proceed predominantly by peripheral (t-channel) interactions, and one may expect the scattering to be dominated by a forward diffraction peak. Indeed, the differential cross section at 65° observed in our experiment of 1.7 GeV gamma rays is about one order of magnitude smaller than the lower limit for the cross section at 0°, deduced from the optical theorem, and the total interaction cross section, inferred from bubble chamber experiments, while the two values are quite comparable for gamma ray energies below about 1 GeV. We are planning measurements at small momentum transfers (about 0.2 GeV/c^2) to observe the rise in the diffraction peak.

A summary of a preliminary evaluation of our results is presented in Fig. 4.1. These results were submitted to the Stanford Conference on Photon Interactions at High Energies. Fig. 4.2 shows a schematic representation of the apparatus as it is currently used. The points shown as circles in Fig. 4.1 were obtained by means of this apparatus. The points marked by

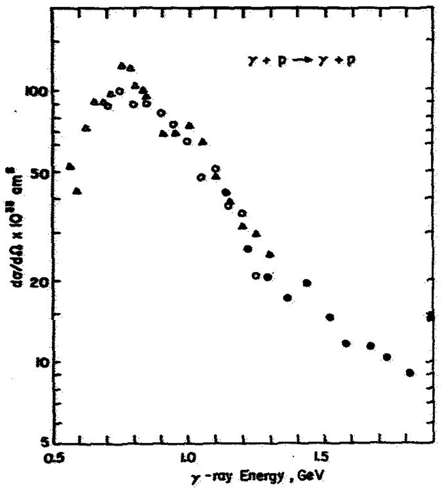

Fig. 4.1

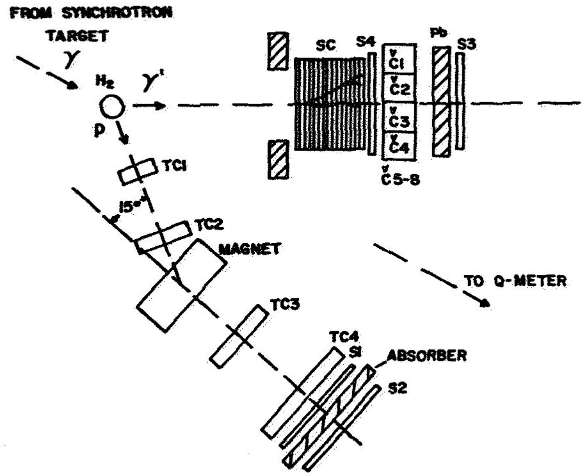

Fig. 4.2

triangles represent data for which the proton energy was measured in a range chamber rather than by the magnetic spectrometer. The open triangles were obtained by us at Cornell in 1962. The black triangles represent the first CEA data. As was reported by us at that time, there was serious doubt concerning the calibration of the quantameter used. In fact, the data represented by the solid triangles were normalized to the overlapping spectrometer data. The normalization showed that the 1963 quantameter calibration was in error by a factor of 1.4, as had been suspected.

Figures 4.3 and 4.4 illustrate the evaluation of the data obtained with the apparatus shown in Fig. 4.2. The kinematics of the process are derived from the direction and momentum of the proton on the assumption that it was an elastic collision and the direction of the scattered gamma ray is calculated with this assumption. In Fig. 4.3 the deviation of the observed gamma ray from the calculated direction is shown for a sample of the data. The elongated central cluster of points contains the elastic scattering events. The extended background is due to pi-zero decays. The width of the central peak in the (horizontal) reaction plane is about four times greater than normal to it, since the coplanarity condition does not involve the error in proton energy measurement. In Fig. 4.4 the data have been reduced to a two-dimensional presentation by plotting the number of events in ellipses of equal area around the center of Fig. 4.3. The number of scattering events is found by subtracting the smooth background from the peak in Fig. 4.4.

The plots in Figs. 4.3 and 4.4 were produced by the PDP-1 data processor and oscilloscope used in the SPASS system. Plots of this kind are used to monitor the scanning procedure. They were photographed by placing unexposed film into the SPASS film transport. (M. Deutsch, P. Marini, P. Patel, K. Tsipis and students)

2. Recoil Polarization in π^0 Photoproduction

A complete phenomenological analysis of pion photoproduction would require measurements of differential cross sections for several separated polarization states of the incident photon, the target and the recoil proton. Measurements at CIT of the latter quantity have shown rapid variations up to the highest photon energies reached (1.4 GeV). Therefore it seemed worth while to extend these measurements to somewhat higher energies.

The apparatus shown in Fig. 4.2 is well-suited to the detection of pi-zero photoproduction. In fact, about 15 times as many pi-zero events appear in Fig. 4.3 as elastic scattering events. Prof. Milburn and collaborators have constructed a large (1 m^3) carbon-plate spark chamber to detect proton polarization by the asymmetry of elastic scattering. This chamber was placed near the exit of the proton spectrometer shown in Fig. 4.2, and some minor changes were made in the counters and collimators used.

About 170,000 events have been photographed for photon energies up to about 1.7 GeV. The recoil proton is identified and its energy measured using the SPASS system. The scattering of the proton in the carbon plates is being analyzed by the Tufts group. The latter procedure is expected to require several months. (M. Deutsch, P. Patel, K. Tsipis, and students; with Prof. R. H. Milburn and collaborators at Tufts University)

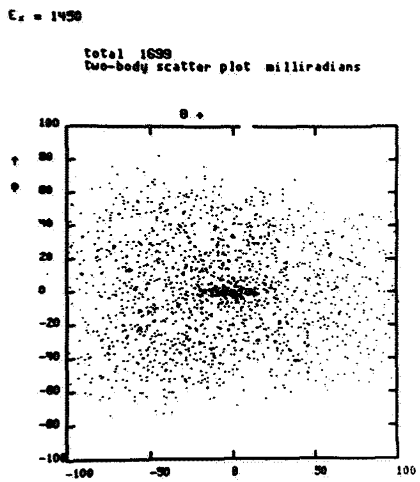

Fig. 4.3

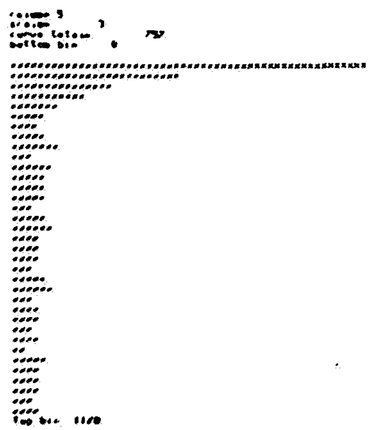

Fig. 4.4

3. Lambda Polarization in K^+ Photoproduction.

This experiment, like the two described above, is conceived initially as a contribution to the phenomenology of the photon energy region between 1.2 and 2 GeV. In principle, the polarization of a lambda hyperon is easier to detect than that of a recoil proton but, because of the preponderance of pion photoproduction over kaon production, more sophisticated methods are required to identify the production process.

We have prepared an exploratory experiment, designed for a limited energy region and moderate data statistics. The kaon will be identified in the magnetic spectrometer of Fig. 4.2 using time-of-flight techniques, and the direction of the decay proton from lambda decay will be observed in a telescope of visual spark chambers and counters, functionally replacing the gamma ray detector in Fig. 4.2. Initial data are expected to be obtained during January 1968. If this experiment is successful we plan to replace all visual spark chambers by directly digitizing wire spark chambers in order to increase the rate of data acquisition and to add a gas Cerenkov counter for kaon identification in order to increase the energy range. All major components for this extension are already available or under development for other experiments, but the development of this experiment will depend on the effort required by the other parts of our program. (J. Cleetus, et al.)

4. Photoproduction of Charged Pions at Large Angles

This experiment is described elsewhere in this report. The contribution of this group consists entirely of the evaluation of the photographs by the SPASS system. (with Prof. R. A. Alvarez and collaborators)

B. K^+ Meson Decays

In collaboration with Dr. R. F. Stiening, Dr. C. Wiegand and coworkers at LRL, Berkeley, about 100,000 decay events of K^+ mesons at rest were photographed in the spark chamber arrangement shown in Fig. 4.5. Fig. 4.6 shows a typical photograph. The four experiments described below are based on these photographs. Our contribution to these experiments is almost entirely at the stage of data evaluation.

1. Form Factors of $K\mu_3$ Decay.

The main aim of the experiment was a determination of the polarization of the muons in the decay $K^+ \rightarrow \pi^0 + \mu^+ + \nu$, by observing the angular distribution of decay electrons in the range chamber shown at the right in Fig. 4.5, together with the direction of the muon and the direction and energy of the pion as determined from the angles and energies of the decay gamma rays observed in the shower chambers surrounding the target. This polarization gives insight into the structure of the decay interaction. It yields a direct measure of the ratio $\xi = f_-/f_+$ of the two conventional terms $f_+(q_K+q_\pi)$ and $f_-(q_K-q_\pi)$ in the decay amplitude. A net component of polarization transverse to the decay plane would indicate an imaginary component of ξ and,

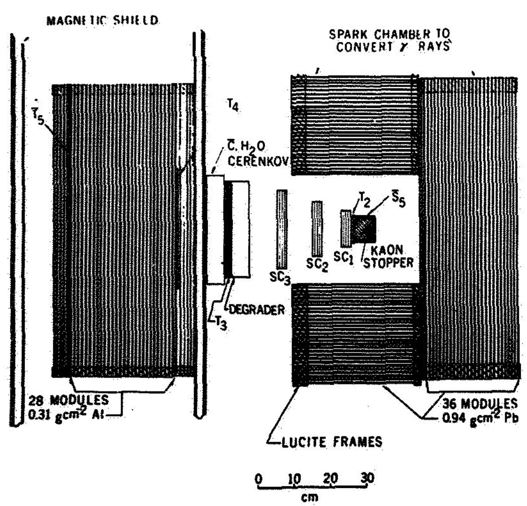

Fig. 4.5

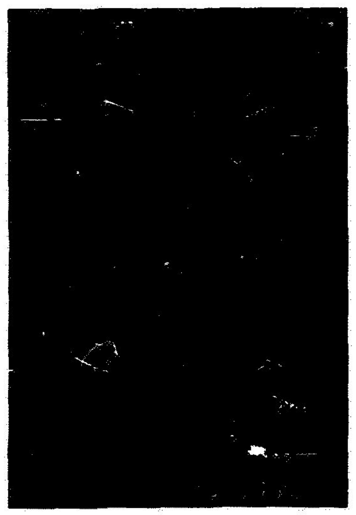

Fig. 4.6

therefore, violation of time reversal invariance. The experimental result is consistent with zero for this component. The longitudinal component of the polarization yields an average value of $\xi = -0.9 \pm 0.3$, and this value shows no marked dependence on the energy sharing between pion and leptons. This result is inconsistent with published measurements of the ratio of decay rates K_{e_3}/K_{μ_3}. It is also difficult to reconcile with current algebra predictions based on the amplitude for $K\mu_2$ decay. We believe that our result is correct within the errors indicated and that other experiments and the theory will have to be reconciled with it. This result is being presented at the November 1967 Princeton Meeting on kaon decays.

2. Search for $K^+ \rightarrow \pi^+ + 2\gamma$.

Several suggestions have been made which would yield a significant decay rate of the kaon into a pion and two gamma rays with an invariant mass far from that of the neutral pion. A search for this process among the photographs obtained in this experiment set an upper limit of the order of 10^{-4} for the fraction of kaons decaying in this manner, the exact limit depending on the energy distribution assumed. This limit rules out some suggestions of an intermediate scalar meson with strong electromagnetic decay which has been invoked to explain the reported high probability of the analogous decay of the η meson. The most interesting suggestion assumes that the dominant $K\pi_2$ decay is inhibited by the $\Delta I = \frac{1}{2}$ rule and that this suppression is much weaker for virtual neutral pions far off the mass shell, since the purity of the final two-pion isospin states is broken by the mass difference. Unfortunately, our upper limit is just consistent with this speculation. Preliminary results of this experiment were presented to the 1967 International Conference on High Energy Physics in Heidelberg. Final results have been submitted to The Physical Review Letters and circulated in a UCRL report (UCRL 17887).

3. Search for $K^+ \rightarrow X^+ + \gamma$

The decay $K \rightarrow \pi + \gamma$ is forbidden by conservation of angular momentum. It has been suggested at various times that a particle of spin 1 with a mass close to that of a pion might be involved in kaon decay. Search of the photographs obtained in these experiments shows that any KX decay mode with 133 MeV $< m_X <$ 148 MeV or 183 MeV $< m_X <$ 202 MeV constitutes less than 3×10^{-5} of all K^+ decay modes if the X particle does not interact strongly with the absorber material and 6×10^{-5} if it does interact strongly. This result will be made available as an LNS Technical Report (No. MIT-2098-389).

4. $K^+ \rightarrow \mu^+ + \nu + \gamma$

Radiative $K\mu_2$ decay is of interest for several reasons, primarily in the context of charge conjugation invariance of the electromagnetic interaction of hadrons. About 25,000 photographs were obtained with a modification of the apparatus shown in Fig. 4.5 designed to enhance the detection of this decay mode. Evaluation of these photographs is in the initial stages.

5. $K^+ \rightarrow \pi^+ + \pi^- + e^+ + \nu$

An experiment to study the $K^+_{e_4}$ decay mode is being prepared. This experiment will throw further light on the structure of the leptonic decay interaction, for example, in the apparent puzzle in the form factor determination discussed under 2 above. The interpretation of the K_{e_4} spectrum also involves the pion final state interaction. The phase-shift interpretation of the corresponding effect in the $K^0\pi_2$ decay has recently led to a paradoxic result concerning the mass difference of the neutral K mesons. We have proposed to perform this experiment at the AGS during the second half of 1968. (K. Tsipis, M. Deutsch and students)

C. SPASS

During the past year, about 750,000 frames of spark chamber photographs were measured by the SPASS system. These photographs contained data for eight experiments involving three distinctly different spark chamber arrangements.

The SPIP program system is now sufficiently versatile to allow us to write the entire program for a new experiment in about a week of intensive effort and to produce valid output after another week of calibration and program modification. The use of a zoom lens in the scanning optics now permits optimum utilization of the scanning oscilloscope area for different frame arrangements without major mechanical adjustments.

The most complex photographs analyzed are illustrated in Fig. 4.6. These photographs contain two views each of nine spark chambers: five tracking chambers, three shower chambers and a range chamber.

For the first time, tracks in wide-gap spark chambers were measured by SPASS. Fig. 4.7 shows a typical event. It was found that the angle of each track segment in the 5-inch wide chambers was measured with a precision of about ± 0.25 degree. It should be noted that these chambers were operated in the "spark mode" rather than in the low-energy mode characteristic of streamer chambers, which permits considerably better precision than is now possible with the SPASS hardware.

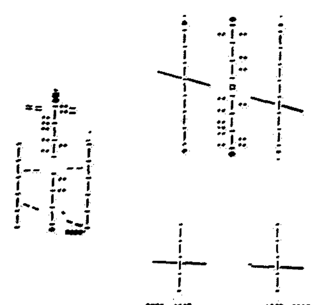

Fig. 4.7

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V. Researches of the J. I. Friedman, H. W. Kendall, et al., Group

A. SLAC Collaboration

Our collaboration with the SLAC spectrometer group is well underway, and now that both the accelerator and the spectrometers are operational we are well into the data-taking phase of our SLAC program. Our group has had the responsibility for the design and construction of the particle detector hodoscopes employed in the 8 and 20 BeV spectrometers constructed for the electron scattering program. The following objectives have been completed during the past year:

1) Completion of detector hodoscopes and their installation in the 8 and 20 BeV spectrometers.

2) Completion and installation of a π-e discriminator which can separate with high efficiency electrons and π^- mesons of the same momentum in the range from about 2 BeV/c to 20 BeV/c.

3) The construction and installation of the electronic logic associated with the detectors and the buffers used in storing the information which is to be read into the on-line computer.

4) The following measurements have been carried out during the past year or soon will be started:

1. Elastic Electron-Proton Scattering.

With the use of the 8 BeV spectrometer we have measured the cross section for elastic electron-proton scattering over a range of squared four momentum transfers from 0.7 to 25 $(\mathrm{BeV/c})^2$. The experiment is being analyzed to yield measurements of the magnetic form factor of the proton G_{Mp} in this range of four momentum transfers. A preliminary analysis has been completed. The experimental measurements of $(G_{Mp})^2$ divided by the square of the dipole form factor are shown in Fig. 4.8 along with the measurements from other laboratories. The results indicate that the magnetic form factor falls as $1/q^4$ at large momentum transfers, where q is the four momentum transfer. These results are not in agreement with the exponential form factor proposed by Yang to describe the process at very large four momentum transfers. The dipole model appears to be a reasonably good fit to the measurements over the entire range of q^2, however there are small but statistically well-established deviations from this model.

Early in 1968 we expect to start the second phase of elastic e-p scattering in which we will measure the electric form factor of the proton, G_{Ep}, to as high a q^2 as is possible. In this program we will also utilize the 8 BeV spectrometer.

2. Inelastic Electron-Proton Scattering.

The intense monochromatic electron beam available at SLAC coupled with the high resolution spectrometers make an ideal facility for studying inelastic e-p scattering. We have completed the data taking portion of the initial part of a long-range program to study the inelastic

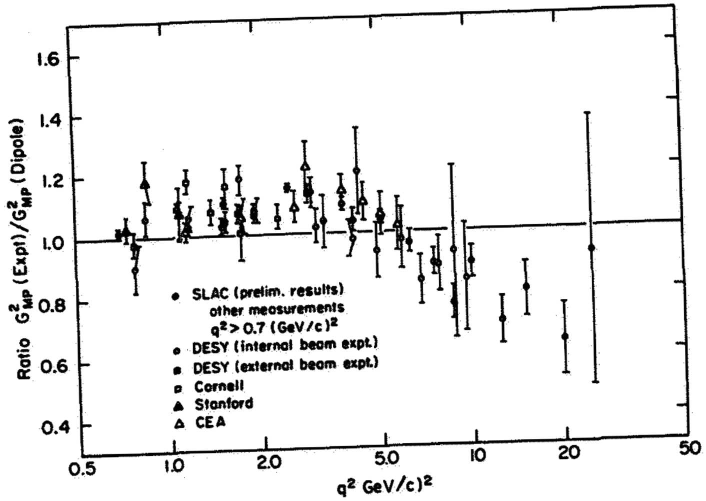

Fig. 4.8

electron spectra from this reaction over the whole range of momentum transfers and inelasticity available at SLAC. The data was taken in order (a) to establish the momentum transfer dependence of the form factors of transitions to excited proton states known to be excited in electron induced reactions; (b) to search for resonances not previously known to be excited in electron scattering; (c) to study the inelastic continuum region to compare with predictions of Bjorken; and (d) to gain a body of data that will allow us to apply and verify a new and complex treatment of radiative corrections. The data reduction procedures have started and it is expected that a preliminary analysis will be completed in time for us to plan carefully for the scheduled machine time which will be devoted to the continuation of this program in the spring. The present data were accumulated using high incident electron energies up to 17 BeV and scattering angles less than 8°. The interpretation of the proton resonant state form factors is simpler for these small angles, and our first searches were accordingly designed to exploit these simplifications in addition to the higher cross sections expected. Approximately 10^7 inelastic events are now awaiting analysis.

The second, and later, inelastic studies will extend the small angle data as may be suggested by the current analysis and in addition will make use of the larger solid angle of the 8 BeV spectrometer to study the very large momentum transfer region both of resonant state excitation and of continuum excitation. In addition we will make feasibility studies of the separation procedures by which magnetic and electric excitations are disentangled. The structure of the inelastic states excited at high momentum transfer is largely unknown at present and our present data suggests that we will be able to study with precision an interesting area of nucleon inelastic structure with the present program.

3. Asymmetric Mu-Meson Pairs.

The MIT-SLAC group has submitted and has had accepted a proposal to study the photoproduction of very asymmetric mu-meson pairs. The reaction is $\gamma + p \to p + \mu^+ + \mu^-$. We detect negative mu-mesons at or near zero degrees with the mu energy virtually equal to the incoming photon energy. The reaction has been studied theoretically by Drell who has shown that an appreciable contribution to the cross section arises from a diagram in which the mu propagator is off the mass shell by an amount very nearly equal to 2 BeV/c at a distance of about 3×10^{-15} cm. The design of the special instrumentation required for the highly precise momentum analysis required to reject unwanted reaction products is now underway. Present scheduling would suggest that the experiment should be running in about October 1968.

B. CEA Experiments

1. Elastic E-D Scattering

We have completed the analysis of measurements carried out at the CEA of the differential cross sections for the elastic scattering of electrons from deuterons in the range of squared four momentum transfers from 0.6 to 1.4 $(\mathrm{BeV/c})^2$. The results are now being written up for publication. The objective of this experiment was to measure the electromagnetic form factor of the deuteron and from this information determine some of the characteristics of the n-p interaction, especially its short range characteristics. We find that the results are consistent with the form factors predicted from some of the modern hard and soft core potentials. The measurements are not compatible with the presence of a mesonic current interaction of the type proposed by Drell and Adler.

2. External Beam Facility at the CEA

The quadrupole spectrometer with which we carried out the elastic electron-deuteron program has been placed in an external electron beam at the CEA. This spectrometer has been implemented with detectors and is now operational as a device to momentum analyze scattered electrons. In addition, a second arm, which will enable us to measure recoil particles in coincidence with the scattered electrons, has been placed on the same pivot and is being prepared for two experiments which are expected to be in the data-taking phase in the early part of 1968. These are the experiments:

a) Elastic Electron-Alpha Particle Scattering. In this experiment we plan to measure the electro-magnetic form factor of the alpha particle up to a squared four momentum transfer of about 1.4 $(\mathrm{BeV/c})^2$ in order to provide information about the

structure of the alpha particle. These measurements will be programmed in such a way as to provide also a limit on possible anomalous structure of the electron. This is done by comparing large and small angle cross sections at a constant four momentum transfer. On the basis of a one photon exchange calculation, this ratio is independent of effects from the α-particle structure, and is sensitive to possible anomalous structure of the electron.

b) Inelastic Electron-Deuteron Scattering. We plan to measure the differential cross section near threshold for electro-disintegration of the deuteron. By measuring at high momentum transfers the spectrum of inelastically scattered electrons in the region of the final state interaction, we hope to learn about the short range characteristics of the unbound n-p system at low relative energies. We expect to make these measurements up to a squared four momentum transfer of about 1.2 $(\mathrm{BeV/c})^2$.

3. Nucleon-Nucleon Correlations.

A study of the inelastic scattering of high energy electrons from Bi-209 has been nearly completed. A collaboration with D. Isabelle of Orsay used the Orsay electron linac in a study designed to extract some knowledge of nucleon-nucleon correlations in Bismuth using the theory of Czyz and Gottfried. In the course of this work we have carried out a new and detailed study of the applications of radiative correction theory to deep inelastic scattering.

4. Phase Shift Analysis of Inelastic Nucleon-Electron Scattering.

The difficult programming task of adapting phase shift solutions of the Dirac equation to electron scattering from nuclei with the excitation of nuclear levels has been completed and is currently being employed to help us understand a quantity of inelastic scattering data. This program, in part written in anticipation of the completion of the MIT Electron Linac, is extremely fast and gives promise of being a very powerful tool in the interpretation and understanding of nuclear excited states and the electron processes that excite them.

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O.N.R. GENERATOR GROUP

I. Introduction

The principal research interests of this group of staff and students are in nuclear spectroscopy and structure. The major experimental equipment consists of an electrostatic accelerator and two magnetic spectrographs of the uniform field, broad-range type. One of these is a multiple-gap instrument especially suited for angular distribution studies.

During the past year, a wide variety of nuclei were studied, ranging from sulfur to tellurium. In most cases the reactions used involved stripping or pickup so that the results could be analyzed to obtain spin and parity assignments and the spectroscopic strengths of the individual levels. Much of this work employed the doubly charged He^3 beam, and particular attention was given to those nuclei in the first $f_{7/2}$ shell. Comparisons of the results of these experiments with theoretical predictions are providing sensitive tests of various nuclear models. Several of the researches carried out were collaborative efforts with groups at other institutions. In these cases the nuclear track plates exposed in the spectrograph were sent to the particular institution for analysis. During the year, such cooperative studies were carried out at Yale, at the Universities of Bergen, Chile, and Mexico, and at Providence College.

Members of the group have also been active in the design and construction of equipment to extend the range of studies that can be carried out with our present accelerator and that could also be used with one or another of the higher energy machines that will come into operation in the not too distant future. In this connection, some studies of high energy heavy ions have been made using nuclear track plates and the MP tandem facility at the High Voltage Engineering Corporation. The results are interesting in themselves and the experience gained will be valuable for future experiments with heavy ions. (T. A. Belote, W. W. Buechner, E. R. Cosman, W. E. Dorenbusch, H. A. Enge, W. H. Moore, J. Rapaport, and A. Sperduto)

II. Studies of Nucleon Structure in the $1f_{7/2}$ Shell

A. Inelastic Deuteron Scattering

Work has continued on the inelastic scattering of deuterons by target nuclei in the $1f_{7/2}$ shell. Present work on he systematics of these nuclei is under way. (Ole Hansen (Copenhagen), T. A. Belote, and W. E. Dorenbusch)

B. The Enriched Calcium Target Experiment

Work has continued on the analysis and interpretation of (d, p) reactions on a special calcium target. The results seem to indicate a departure from the simple-shell model sum rule. (W. E. Dorenbusch, Ole Hansen (Copenhagen), J. Rapaport, and T. A. Belote)

C. Even Parity States in Ca^{41} and Ca^{43}

1. The $K^{39}(He^3, p)Ca^{41}$ Reaction. A report of this work along with a letter on the preliminary results have been published.[1,2] This reaction was found to strongly excite unnatural parity levels of Ca^{41} of (2p - 1h) character. The reaction was dominated by strong L = 0 transitions. The results were analyzed using both JULIE and the two-nucleon transfer formalism of Glendenning.[3] The procedure is indicated in Fig. 5.1. The results were interpreted using the calculated results of Sartoris and Zamick[4] and it was found that a good correspondence existed between the experiment and calculated level scheme. An analysis of the data was also carried out in order to look for intermediate structure or suggested by Bolsterli, et al.[5] The results obtained using this procedure are shown in Fig. 5.2. (T. A. Belote, F. T. Dao, W. E. Dorenbusch, J. Kuperus, S. M. Smith, and J. Rapaport)

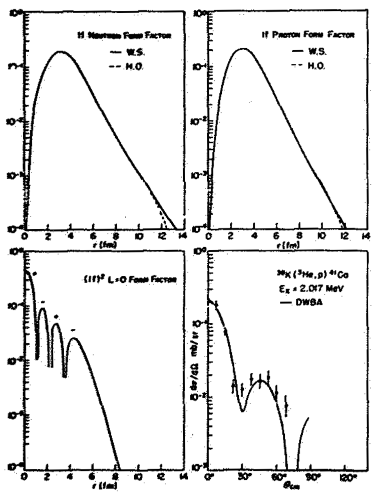


Fig. 5.1

1. T. A. Belote, F. T. Dao, W. E. Dorenbusch, J. Kuperus, and J. Rapaport, Phys. Letters 23, 480 (1966).
2. T. A. Belote, F. T. Dao, W. E. Dorenbusch, J. Kuperus, S. M. Smith, and J. Rapaport, Nuclear Phys. A102, 462 (1967).
3. N. K. Glendenning, Phys. Rev. 137, B102 (1965).
4. G. Sartoris and L. Zamick, Phys. Rev. Letters 18, 292 (1967).
5. M. Bolsterli, W. R. Gibbs, A. K. Kerman, and J. E. Young, Phys. Rev. Letters 17, 878 (1966).

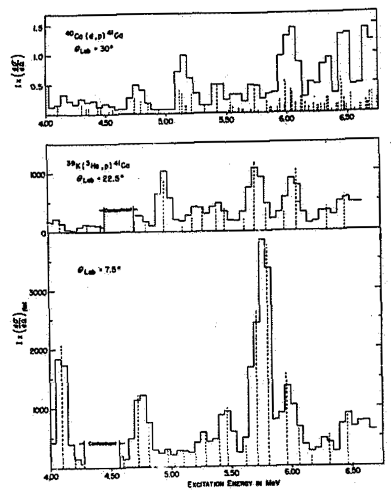


Fig. 5.2

2. The $K^{41}(He^3, p)Ca^{43}$ Reaction. The $K^{41}(He^3, p)Ca^{43}$ reaction was used to investigate the hole states of Ca^{43}. The reaction was initiated with a He^3 beam of 13 MeV incident onto a K^{41} target with a thickness of 78 $\mu g/cm^2$. Preliminary results indicate that only the T=5/2 isobaric analog state at 7.98 MeV is strongly excited in this reaction. The differential cross sections at $\theta = 7.5°$ of various levels can be seen from Fig. 5.3, which includes results from the previous $K^{39}(He^3, p)Ca^{41}$ reaction. The 4p - 1h strengths in Ca^{43} are apparently not as strong as the corresponding 2p - 1h strengths in Ca^{41}. Of the two low-lying $J=3/2^+$ states in Ca^{43}, the 0.990-MeV anti-isobaric analog state is only weakly excited while the 1.393-MeV state is not observed. (W. E. Dorenbusch, F. T. Dao, T. A. Belote, and J. Rapaport.)

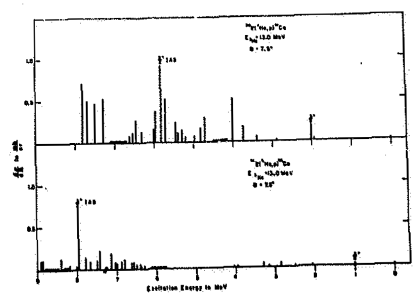


Fig. 5.3

D. (He^3, d) Reaction Studies on Even Nuclei

1. Stripping Transitions in $^{46}Ti(^3He, d)^{47}V$. The $^{46}Ti(^3He, d)^{47}V$ reaction has been studied at a bombarding energy of 12.0 MeV. The measured deuteron spectrum at a laboratory angle of 52.5 deg is shown in Fig. 5.4. Eighteen transitions below 5.65 MeV of excitation were analyzed in the distorted-wave approximation to yield ℓ_p values and spectroscopic strengths. Fig. 5.5 shows angular distributions for the ground ($3/2^-$), first excited ($5/2^-$), and second excited ($7/2^-$) states. The solid curves are the DW calculations. The level scheme information provided by the present work is summarized in Fig. 5.6. Values of $(2J+1)C^2S$ are plotted on a logarithmic scale versus excitation energy. The analogues of the $1f_{7/2}$ state and first $2p_{3/2}$ state of ^{47}Ti seen in the $^{46}Ti(d, p)^{47}Ti$ reaction[1] are indicated by the dashed lines. The $1f_{7/2}$ Coulomb displacement energy calculated from the excitation energies of the $J^\pi=7/2^-$, T=3/2 analogues is 7.835 ± 0.020 MeV. Energy levels from $^{50}Cr(p, \alpha)^{47}V$ are also shown.[2]

This paper has now appeared in Nuclear Physics A102, 681 (1967). (W. E. Dorenbusch, J. Rapaport, and T. A. Belote)

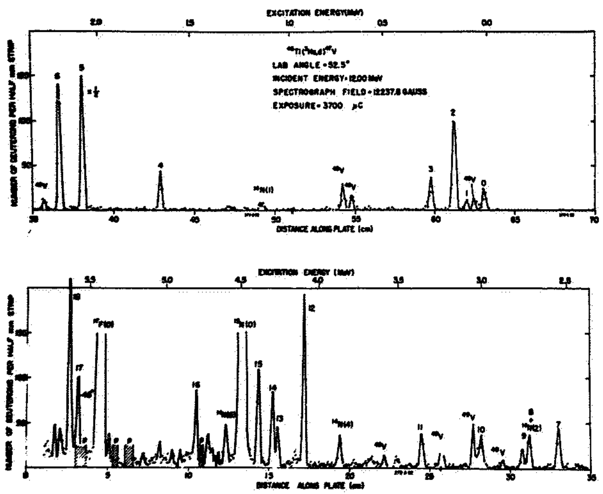


Fig. 5.4

1. J. Rapaport, A. Sperduto, and W. W. Buechner, Phys. Rev. 143, 808 (1966).
2. G. Brown, A. MacGregor, and R. Middleton, Nuclear Phys. 77, 385 (1966).

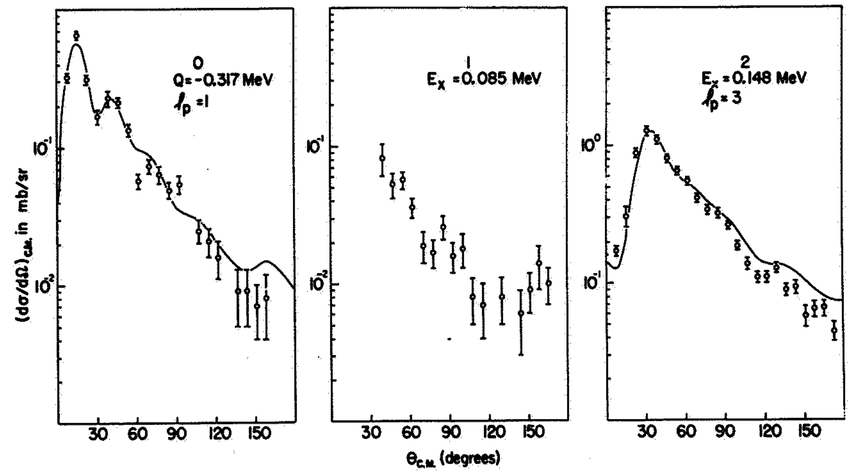


Fig. 5.5

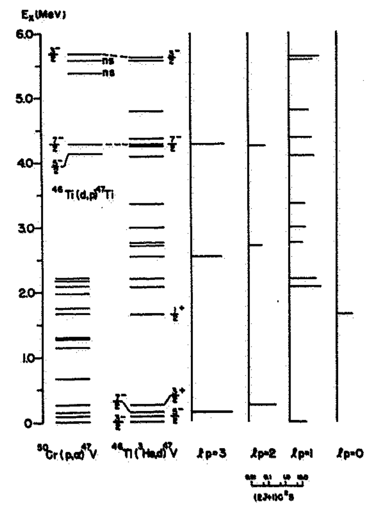


Fig. 5.6

2. The $^{50}Cr(^{3}He,d)^{51}Mn$ Reaction. The reaction $^{50}Cr(^{3}He,d)^{51}Mn$ has been investigated at 12.0-MeV bombarding energy using the MIT multiple-angle spectrograph. A DWBA analysis has been carried out on the angular-distribution data for 29 levels below 5.7 MeV of excitation to determine ℓ_p values and spectroscopic strengths. The transition to the $5/2^-$ ground state has been compared with shell-model forbidden $5/2^-$ transitions to ^{47}V, ^{51}V, and ^{53}Mn (see Fig. 5.7). The analogue of the ^{52}Cr ground state was observed at $E_x = 4.446$ MeV with an $\ell_p=3$ angular distribution; the corresponding Coulomb displacement energy was determined to be $\Delta E_c = 8.423 \pm 0.015$ MeV. The level structure of ^{51}Mn is presented in Fig. 5.8. (J. Rapaport, T. A. Belote, and W. E. Dorenbusch)

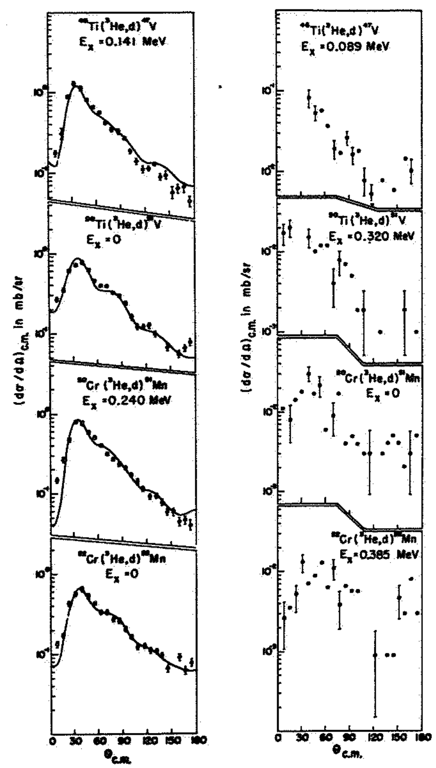


Fig. 5.7

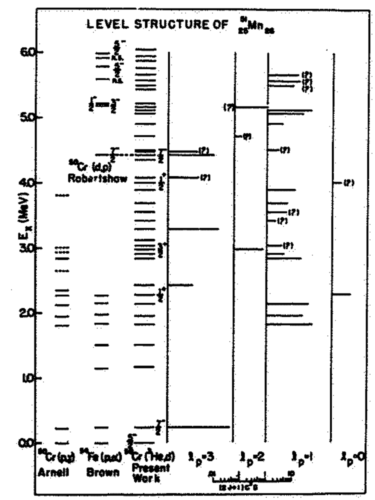


Fig. 5.8

3. The $Cr^{54}(He^{3},d)Mn^{55}$ Reaction. A 4000 μC exposure at 10-MeV incident energy was done on a 98% enriched Cr^{54} target. Scanning of the plates to measure the deuteron angular distributions is now in progress. (R. Doering, J. Rapaport, T. A. Belote, and W. E. Dorenbusch)

4. (He^3,d) Reactions on N=28 Nuclei. The $Ti^{50}(He^3,d)V^{51}$, $Cr^{52}(He^3,d)Mn^{53}$, and $Fe^{54}(He^3,d)Co^{55}$ reactions were investigated using incident He^3 ions of 10, 11, and 12 MeV, respectively. The observed spectrum at $\theta_{Lab} = 52.5°$ is shown in Fig. 5.9 for the $Ti^{50}(He^3,d)V^{51}$ reaction and the angular distribution for the low-lying levels are presented in Fig. 5.10. A distorted-wave analysis of these data was carried out to obtain ℓ_p values and strengths. The level scheme for V^{51} and Mn^{53} are shown in the form of a strength function diagram in Fig. 5.11 and 5.12 and are compared with the calculated level scheme of Auerbach[1] in Fig. 5.13. The results of this experiment have been submitted for publication to Nuclear Physics. (B. J. O'Brien, W. E. Dorenbusch, T. A. Belote, and J. Rapaport)

1. N. Auerbach, Phys. Letters 24B, 260 (1967).

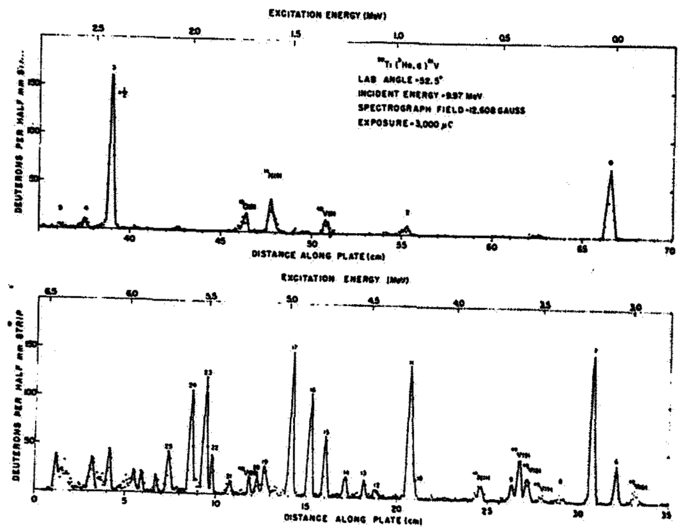


Fig. 5.9

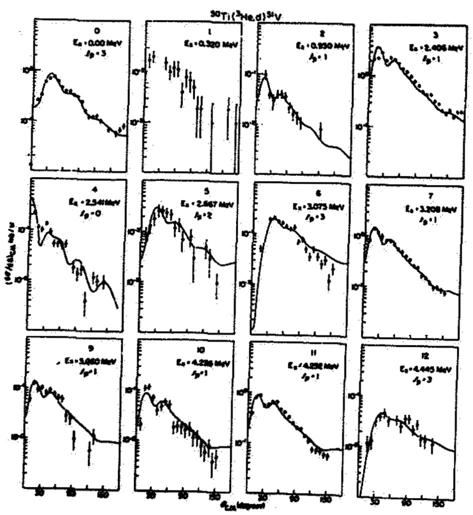


Fig. 5.10

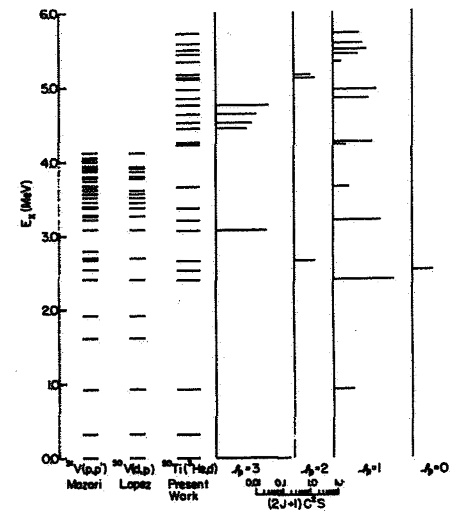


Fig. 5.11

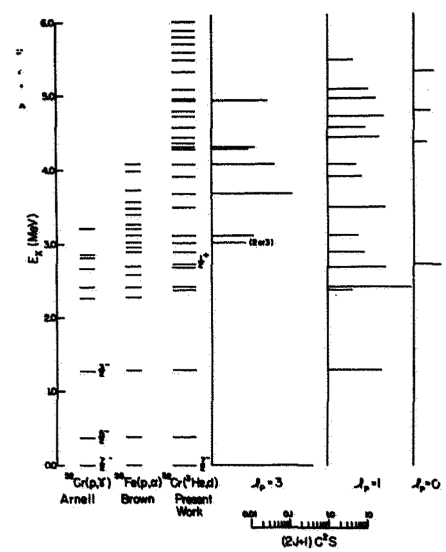


Fig. 5.12

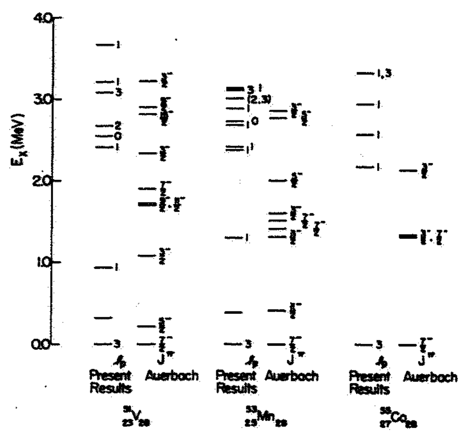


Fig. 5.13

E. Level Structure of Ti^{47} and Cr^{53}

A large-transmission, charged-particle spectrometer[1] with good resolving power together with conventional fast-coincidence scintillation techniques was employed to investigate the gamma decay modes of the excited states in Ti^{47} and Cr^{53}. The nuclear levels were excited by inelastic proton scattering, and the gamma-rays from the de-excitation of the levels were observed in coincidence with the inelastically scattered proton groups. The information thus obtained, concerning the spins and parities of the excited states, supplemented other data obtained by means of single nucleon transfer reactions.

The levels in Ti^{47} were studied by the neutron pick-up reaction $Ti^{48}(He^3, \alpha)Ti^{47}$. Because of the high Q value (8.960 MeV) of this reaction, it was possible to identify excited levels at 7.31, 8.11, and 8.72 MeV which are the T=5/2 isobaric analogues to the $7/2^-$ ground state and the $3/2^+$ and $1/2^+$ hole states at 0.765 and 1.392 MeV in Sc^{47}. Attempts have been made to fit the angular distributions of the alpha-particles from these and other excited levels in Ti^{47} to the distorted-wave-Born-approximation (DWBA) calculations.

The levels in Cr^{53} up to an excitation of 4.70 MeV were investigated by the deuteron stripping reaction on Cr^{52}. The DWBA theory was used to obtain the transferred neutron angular momenta and the other spectroscopic information on the levels in Cr^{53}. Data obtained

1. D. L. Smith and H. A. Enge, MIT Report 2098-276.

on the levels in Cr^{53} up to an excitation energy of about 1.5 MeV, by means of the inelastic proton and deuteron scattering by Cr^{53}, have also been studied. The excitation energies, the spins and parities of the levels, and the spectroscopic factors have been compared with the predictions of different theoretical calculations on the spectroscopy of nuclei with $20 \leq Z \leq 28$, N = 29. It is found that the excitation energies of the low-lying levels in Cr^{53} and the fragmentation of the $\nu p_{3/2}$, $\nu p_{1/2}$, and $\nu f_{5/2}$ neutron single-particle strengths within these states in the (d, p) reaction on Cr^{52} are reasonably well explained by a coupling of the 29th neutron in the $\nu p_{3/2}$, $\nu p_{1/2}$, and $\nu f_{5/2}$ orbits to the even parity states of the cores. (M. N. Rao and J. Rapaport)

F. (He^3, d) Reactions on Odd Nuclei

1. The $Sc^{45}(He^3, d)Ti^{46}$ Reaction. A 50 $\mu g/cm^2$ Sc^{45} target was bombarded with 7.0 MeV He^{3+} and the deuteron groups obtained from a 15,000 μC exposure were recorded on nuclear plates in the multiple-gap spectrograph. This reaction was done at such a low bombarding energy because the Q value for the ground-state transition is Q_0=4.857 MeV and the maximum deuteron energy that can be analyzed in the multiple-gap spectrograph is 12 MeV. The observed groups in Ti^{46} have a rather low yield. Work is now in progress. (D. Bainun, W. E. Dorenbusch, T. A. Belote, and J. Rapaport)

2. The $^{47}Ti(^3He, d)^{48}V$ Reaction. Data have been taken at 11 MeV over the full range of scattering angles. The scanning has been completed, and ℓ_p values and spectroscopic strengths have been extracted from the measured angular distributions. The results are being interpreted in terms of shell-model calculations. Low-lying $1f_{7/2}$ transitions are presently being analyzed in terms of the multipole sum rules[1] together with the results[2] of the analogue reaction $^{47}Ti(d, p)^{48}Ti$. (K. G. Nair, W. E. Dorenbusch, T. A. Belote, and J. Rapaport)

3. The $^{50}V(^3He, d)^{51}Cr$ Reaction. Proton transfer on ^{50}V is being investigated at a bombarding energy of 7.5 MeV. An exposure of 35,000 μC has been taken on an isotope separated target. Scanning is now in progress. (S. M. Neirman, W. E. Dorenbusch, J. Rapaport, and T. A. Belote)

G. Neutron Pickup Reaction

1) The $Sc^{45}(He^3, \alpha)Sc^{44}$ Reaction. An exposure of 7,500 μC was done at 13.0 MeV incident energy and the alphas were detected in Ilford KO emulsions using the multiple-gap spectrograph. Scanning of the plates is now in progress. (D. Bainun, W. E. Dorenbusch, T. A. Belote, and J. Rapaport)

1. J. B. French, Phys. Letters 13, 247 (1964).
2. P. D. Barnes, C. K. Bockelman, O. Hansen, and A. Sperduto, Phys. Rev. 138, B597 (1965).

2) The $Fe^{54}(He^3, \alpha)Fe^{53}$ Reaction. The energy levels of Fe^{53} have been studied by means of the $Fe^{54}(He^3, \alpha)Fe^{53}$ reaction. A 97 percent enriched Fe^{54} target of 48 $\mu g/cm^2$ thickness was bombarded with 13-MeV He^{3++}. Alpha angular distributions were measured for seventeen excited states in Fe^{53} including three analogue states (IAS) of Mn^{53}. The IAS of the Mn^{53} ground state was observed at $E_x = 4.24$ MeV; the IAS of the $2s_{1/2}$ hole state in Mn^{53} at 2.720- MeV excitation was observed at $E_x = 7.02$, while the IAS of the $1d_{3/2}$ hole state in Mn^{53} at 3.010-MeV excitation was observed at 7.25-MeV excitation.

This work has been made in conjunction with Prof. Alex Trier and Prof. Lincoyan Gonzalez at the Universidad de Chile, Santiago, Chile. (J. Rapaport, T. A. Belote, and W. E. Dorenbusch)

H. (He^3, p) Reactions

1) Level Structure of ^{48}V. Energy levels in ^{48}V up to 3.7 MeV of excitation were identified from the reactions $^{46}Ti(^3He, p)^{48}V$ and $^{50}Cr(d, \alpha)^{48}V$. Alpha particles from the (d, α) reaction were recorded at eight angles over the range from 15 deg to 172.5 deg in 22.5 deg intervals. The bombarding energy was 7.0 MeV. Forty transitions belonging to mass 48 were observed. The Q value for the ground-state transition was determined to be 4.923 ± 0.015 MeV. Most of the states seen in the (d, α) reaction were only weakly excited in the $(^3He, p)$ reaction at 12.0 MeV. The stronger $(^3He, p)$ transitions have angular distributions strongly peaked in the forward direction. These transitions were analyzed to obtain values of the transferred angular momentum. The transition to the ^{48}Ti ground-state analogue was observed and the ^{48}V-^{48}Ti Coulomb energy difference was found to be $\Delta E_c = 7.913 \pm .025$ MeV. A manuscript is presently being prepared. (W. E. Dorenbusch, T. A. Belote, and J. Rapaport)

2) Level Structure of ^{52}Mn. The level structure of ^{52}Mn has been investigated by the $^{50}Cr(^3He, p)^{52}Mn$ and $^{54}Fe(d, \alpha)^{52}Mn$ two-nucleon transfer reactions. Twenty-nine levels were excited by the (d, α) reaction up to 3.9 MeV. For the $(^3He, p)$ reaction, angular distributions of eight levels below 5.5 MeV were measured. A ground-state Q value of 5.159 ± 0.015 MeV was determined for the (d, α) reaction. The isobaric analogue of the ^{52}Cr ground state was identified as the E_x=2.95 MeV level, thus yielding a Coulomb displacement energy of $\Delta E_C = 8.435 \pm 0.025$ MeV. (J. Rapaport, W. E. Dorenbusch, and T. A. Belote)

3. Excitation of Co^{56} by Two-Particle Transfer Reactions. The reactions $Fe^{54}(He^3, p)Co^{56}$ and $Ni^{58}(d, \alpha)Co^{56}$ have been carried out at 12.0 and 7.0 MeV, respectively. Ground-state Q values of 7.408 ± 0.015 MeV for the (He^3, p) and 6.506 ± 0.010 MeV for the (d, α) reactions were measured. Angular distributions for eight of the (He^3, p) transitions were measured and analyzed using the DWBA to extract L values. The analogue of the Fe^{56} ground state was identified as well as its anti-analogue at 1.453 MeV. The $Fe^{54}(He^3, p)Co^{56}$ reaction was found to excite mainly states in Co^{56} that are believed to have a large (2p-2h) strength. A paper describing

this work is in preparation. (T. A. Belote, W. E. Dorenbusch, and J. Rapaport)

4. The $Sc^{45}(He^3, p)Ti^{47}$ Reaction. A 50 $\mu g/cm^2$ Sc^{45} target was bombarded with 12.0 MeV He^{3++} particles. Proton groups obtained from a 9,000 μC exposure were recorded in nuclear emulsions in the multiple-gap spectrograph. Scanning of the nuclear plates is in progress. (M. N. Rao, J. Rapaport, W. E. Dorenbusch, and T. A. Belote)

5) The $Ti^{48}(He^3, p)V^{50}$ Reaction. The Kodak NTA plates used to study the $Ti^{48}(He^3, \alpha)Ti^{47}$ reaction have been scanned to study proton groups corresponding to states in V^{50}. This reaction was done at 13.0 MeV and a 3,000 μC exposure was taken on an enriched Ti^{48} target. Scanning of the plates is now in progress. (M. N. Rao, W. E. Dorenbusch, T. A. Belote, and J. Rapaport)

III. The $Fe^{57}(d, p)Fe^{58}$ Reaction

The data for this reaction has been taken at 7.0 MeV bombarding energy with a 3,000 μC exposure. The scanning of the plates, as well as the analysis of this reaction, will be made in collaboration with Prof. Alex Trier and Prof. Lincoyan Gonzalez at the Universidad de Chile, Santiago, Chile. (J. Rapaport, T. A. Belote and W. E. Dorenbusch)

IV. (He^3, p) Reactions on Nickel Isotopes

Five isotopes of copper have been studied experimentally through (He^3, p) reactions on the stable isotopes of nickel. A 13-MeV doubly ionized beam from the MIT-ONR Van de Graaff generator was used to bombard thin targets of Ni^{58}, Ni^{60}, Ni^{61}, Ni^{62}, and Ni^{64}, respectively. The outgoing protons were analyzed in the MIT multiple-gap magnetic spectrograph.

Analysis is in progress on the results of these experiments. Thus far, the stronger low-lying states in Cu^{60} and Cu^{62} have been identified and L-values have been assigned, where possible. The isobaric analogues of the ground states of Ni^{60} and Ni^{62} were seen at excitation energies of 2.536 MeV and 4.610 MeV in Cu^{60} and Cu^{62}, respectively. The ground state Q values were found to be 5.746 ± 0.020 MeV for the $Ni^{58}(He^3, p)Cu^{60}$ reaction and 5.960 ± 0.020 for the $Ni^{60}(He^3, p)Cu^{62}$ reaction. (H. J. Young and J. Rapaport)

V. The $Co^{59}(He^3, p)Ni^{61}$ Reaction

The $Co^{59}(He^3, p)Ni^{61}$ reaction has been done at a 11.7 MeV using the MIT multiple-gap spectrograph. Forty-two transitions were identified below 5.5-MeV excitation in Ni^{61} and the resulting levels were compared with the higher resolution results of the $Ni^{60}(d,p)Ni^{61}$ reaction.[1] Angular distributions for twenty prominent proton groups were extracted and, although no detailed DWBA analysis was performed, the presence of L=0 amplitudes was tentatively deduced. The positions of possible proton core-excited states of two-particle, one-hole character were suggested. They were used to compare with enhancements found in the $Ni^{60}(d,p)Ni^{61}$ "non-stripping" strength function,[1] which have been interpreted by Bolsterli, et al.,[2] as possible evidence of intermediate structure. (E. R. Cosman, D. N. Schramm, and H. A. Enge)

VI. The $P^{31}(He^3,d)S^{32}$ and $P^{31}(He^3,p)S^{33}$ Reactions

Exposures were made for these reactions at an incident energy of 12 MeV. The reaction deuterons and protons were detected at 24 angles on 50-micron nuclear emulsion plates in the multiple-gap spectrograph. Scanning of these plates is now in progress. (E. R. Cosman and A. Sperduto)

VII. The $Zn^{66}(d,p)Zn^{67}$, $Zn^{67}(d,d')Zn^{67}$, and $Zn^{67}(p,p'\gamma)Zn^{67}$ Reactions

Analyses of data from the $Zn^{66}(d,p)Zn^{67}$, $Zn^{67}(d,d')Zn^{67}$, and $Zn^{67}(p,p'\gamma)Zn^{67}$ reactions have been completed, and the results[3] were presented at the Washington meeting of the American Physical Society. The gamma decay modes from the 0.98-, 1.14-, and 1.52-MeV states were examined, confirming ℓ_n value assignments for the even parity states and establishing the strong ℓ_n=1 state at 0.388 MeV as $J^{\pi}=3/2^-$. There is therefore considerably more $2p_{3/2}$ strength than was indicated in our preliminary analysis (see October 1966 Progress Report, page 60). Further examination of the 7.5-MeV $Zn^{67}(d,d')Zn^{67}$ data indicates that the reaction mechanism is not sufficiently clear at this energy to permit a meaningful analysis of the angular-distribution data. A manuscript covering our results from these three reactions is in preparation. (W. H. Moore and H. A. Ismail)

1. E. R. Cosman, D. N. Schramm, H. A. Enge, A. Sperduto, and C. H. Paris, to be published in Phys. Rev.
2. M. Bolsterli, W. R. Gibbs, A. K. Kerman, and J. E. Young, Phys. Rev. Letters 17, 878 (1966).
3. W. H. Moore and Hosni A. Ismail, Bull. Am. Phys. Soc., 12, 493 (1967).

VIII. The Analogue States of Sr^{89}

The analogue state study started at MIT[1] has been continued using the University of Pennsylvania tandem accelerator. Thin Sr^{88} targets were bombarded with protons from E_p = 7.0 to 8.5 MeV and the reaction protons were detected at nine angles simultaneously in a 24-inch diameter scattering chamber. Elastic resonances were fitted with Breit-Wigner curves, and the results compared to those from the $Sr^{88}(d,p)Sr^{89}$ reaction.[2] The $p'(2_1^+)$ channel resonated at 7.0, 7.07, 7.5, 7.72, 7.79, 7.92, 8.2, 8.35, and 8.49 MeV, and the $p'(3_1^-)$ at 7.67, 7.8, 7.92, and (7.49) MeV. Detailed angular-distribution measurements were made for the $p'(2_1^+)$ and $p'(3_1^-)$ groups at the strongest resonances. Weak nonstripping states found in the $Sr^{88}(d,p)Sr^{89}$ study probably correspond to p' resonances at 7.67 and 7.92 MeV that are not accompanied by elastic resonances. The analogue of a $g_{7/2}$ level in Sr^{89} occurring at E_p=7.79 MeV is shifted up by about 70 keV from its expected position relative to the ℓ=2 resonances. Figure 5.14 shows the excitation function data and Table 5.I gives a summary comparison of all our available analogue state data with previous $Sr^{88}(d,p)Sr^{89}$ results.[2] (E. R. Cosman, J. M. Joyce (Univ. of Pennsylvania), and S. M. Shafroth (Bartol Research Foundation))

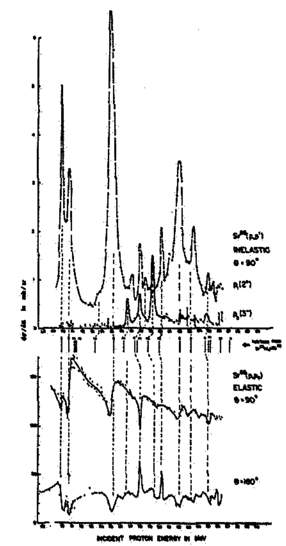


Fig. 5.14

1. E. R. Cosman, H. A. Enge and A. Sperduto, Phys. Letters 22, 195 (1966).
2. E. R. Cosman, H. A. Enge and A. Sperduto, Phys. Rev., to be published.

Table 5.I

A comparison of the Sr^{88}(p,p) and (p,p') results with those from the $Sr^{88}(d,p)Sr^{89}$ reaction. E_p(CM) stands for the center-of-mass proton energy at the center of the analogue resonance considered. E_x' is the difference between E_p(CM) for the resonance and $E_p(0)$=4.999 MeV, corresponding to the ground-state analogue. Γ_{tot} is the total width of the state as determined either by the Breit-Wigner fits to the elastic data or by the observed half-width of the inelastic resonant shape, and Γ_p is the elastic proton width. θ_n^2 is the analogue neutron reduced width calculated by the equation written beneath the table, where P_ℓ is the penetrability and $m_pR^2/\hbar^2$ is the single-particle reduced width. ΔE_x refers to the difference $E_x - E_x'$. The spins J^π quoted are explained in the table footnotes. However, only in the case of level No. (0) has this quantity actually been measured.

$Sr^{88}(d,p)Sr^{89}$ (ref. 1)				Sr^{88}(p,p) abd (p,p') Present Work						
Level no.	E_x ±0.008 (MeV)	ℓ_n, J^π	$S_{\ell,j}$	E_p(CM) ±0.015 (MeV)	E_x' ±0.015 (MeV)	Γ_{tot} (keV)	Γ_p (keV)	θ_n^2	Proton Decay Channel	ΔE_x (MeV)
0	0	$2, 5/2^{+a)}$	0.79	4.999	0	16	8	1.20	E1, 2^+	0
1	1.031	$0, 1/2^{+b)}$	0.90	5.993	0.994	70	46	0.96	E1, 2^+	+0.037
2	1.460	n.s.				n.s.				
3	1.931	$2, 5/2^{+b)}$	0.091	6.914	1.915	50	11	0.30	E1, 2^+	+0.016
4	2.000	$2, 3/2^{+b)}$	0.45	6.983	1.984	50	23	0.63	E1, 2^+	+0.016
5	2.057	n.s.				n.s.				
6	2.071	n.s.				n.s.				
7	2.266	n.s.		7.292	2.298				(2^+)	(-0.032)
8	2.455	$2, 3/2^{+b)}$	0.34	7.415	2.416	60	18	0.30	E1, 2^+	+0.039
9	2.558	n.s. $(3/2^+)^{c)}$		7.578	2.579	30			3^-	-0.021
-	Not seen			(7.628)	(2.629)	30			2^+	
10	2.671	$4, 7/2^{+b)}$	0.74	7.704	2.705	20	4.0	0.57	E1, $2^+, 3^-$	-0.034
11	2.691	n.s.		7.756	2.757	25			(2^+)	-0.058
12	2.805	$(2)(3/2^+)^{d)}$	0.035	7.835	2.836	30			(E1)$2^+, 3^-$	-0.031
13	2.918	n.s. $(5/2^-, 7/2^-)^{d)}$		7.929	2.930	25			E1, 2^+	-0.012
14	3.128	$2, (3/2^+)^{e)}$	0.079	8.099	3.100	40	5.6	0.076	E1, $2^+ (3^-)$	+0.028
15	3.245	$2, (5/2^+)^{e)}$	0.043	8.216	3.217	50	3.0	0.040	E1, 2^+	+0.028
15*	Not seen			8.246	3.247				2^+	
16	3.390	$(4), 7/2^{+b)}$	0.081	8.401	3.402	40	(2.8)	(0.240)	E1, $2^+, 3^-$	-0.012

$$\theta_n^2 = (2T_0+1)\frac{\Gamma_p}{2P_\ell} \cdot \frac{m_p R^2}{\hbar^2}, \quad R = 1.25\, A^{1/3}\text{fm}.$$

a) A measured spin, Nuclear Data Sheets, compiled by K. Way, et al.
b) Deduced from $Sr^{88}(d,p)Sr^{89}$, ref. 2).
c) $Rb^{89}(\beta,\gamma)$ decay, J. E. Kitching and M. W. Johns, Can. J. Phys. 44, 2661 (1966).
d) Deduced from present work
e) Arbitrarily assumed values

IX. Particle-Hole States at N=50 and the $Sr^{87}(d,p)Sr^{88}$ Reaction

The $Sr^{87}(d,p)Sr^{88}$ reaction was carried out at 7.5-MeV incident energy, and scanning of the nuclear track plates to obtain angular distributions is nearly completed. The yields to all states below 4.5-MeV excitation is extremely small indicating little admixture of configurations built from a $2d_{5/2}$, $3s_{1/2}$, $2d_{3/2}$, or $1g_{7/2}$ neutron coupled to a $1g_{9/2}$ neutron hole in the low-lying levels of Sr^{88}. Above 4.5-MeV excitation are seen some very intense ℓ_n=0 and 2 transitions. The fragmentation of these states appears small and they are believed to be relatively pure particle-hole excitations of the magic N=50 core. A DWBA analysis of data is presently being carried out. (E. R. Cosman and D. Slater)

X. The Energy Levels of Ag^{108} from the $Ag^{107}(d,p)Ag^{108}$ Reaction

The study of the energy levels and properties of the odd-even and odd-odd nuclei in the intermediate mass region is exceedingly complicated, and the level schemes are characterized by high level density. In the case of the silver isotopes, level schemes have been investigated from beta-decay work, inelastic scattering and (n,γ) reactions, and in most cases, only the properties of a few states below 1 MeV have been reported.

In the present investigation, an effort to determine the parity and possible spins of levels in Ag^{108} is being undertaken. The data has been obtained with the multiple-gap spectrograph and the scanning of nuclear emulsions and data reduction is being carried out in collaboration with personnel of the Van de Graaff Laboratory at the University of Mexico. A preliminary analysis of the first 46 levels in Ag^{108} up to 1.8 MeV was presented at the Toronto meeting of the American Physical Society in June.[1]

With Ag^{107} having spin and parity of $1/2^-$, and assuming the (d,p) reaction should populate low-lying levels in the shell-model orbitals, $1g_{7/2}$, 2d, and 3s, then neutron capture with ℓ_n = 0, 2, and 4 should be favored and hence pairs of negative parity states. The ground-state spin and parity of Ag^{108} is 1^+ and is most probably formed from the coupling of a $d_{5/2}$ neutron with the 93 keV $7/2^+$ isomeric state in Ag^{107}. Thus pairs of positive parity states might also be expected. The latter are more readily observed by measurements of direct gamma transitions following s-neutron capture in Ag^{107}. The present high resolution (d,p) data affords an interesting comparison with a recent high precision (n,γ) experiment.[2]

Fig. 5.15 shows the positions and relative intensities of (n,γ) level scheme along with those observed in the present (d,p) experiment. It is observed that strong levels excited in the (d,p) reaction are either weak or not observed in the (n,γ) measurements (M1 transitions), and strong (n,γ) transitions (E1) are either weakly excited or not at all in the (d,p) experiment.

1. M. O. De Lopez, M. Mazari, A. Sperduto, and W. W. Buechner, Bull. Am. Phys. Soc. 12 697 (1967).
2. H. H. Bolotin and A. I. Namenson, Phys. Rev. 157, 1131 (1967).

Distorted wave calculations and matching to the data to extract ℓ values from the angular distributions is currently in progress. (M. O. De Lopez, M. Mazari, A. Sperduto and W. W. Buechner)

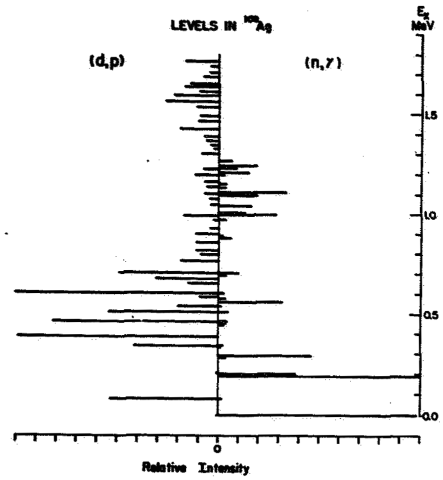


Fig. 5.15

XI. (d, p) Reactions on Tellurium Isotopes

A program of 7.5-MeV (d, p) studies on tellurium is well under way in cooperation with Dr. A. Graue and his co-workers at the University of Bergen, Bergen, Norway. Manuscripts on $Te^{130}(d,p)Te^{131}$ (104 levels observed; 39 angular distributions analyzed)[1] and on $Te^{128}(d,p)Te^{129}$ (87 levels observed; 27 angular distributions analyzed)[2] are scheduled to be published shortly in Nuclear Physics. Data on $Te^{126}(d,p)Te^{127}$, $Te^{125}(d,p)Te^{126}$, $Te^{124}(d,p)Te^{125}$, and $Te^{122}(d,p)Te^{123}$ have been taken. At this time, the Te^{126} data have been scanned and are being analyzed. The Te^{125} data are inadequate, and the experiment will be repeated using a longer beam exposure and a target having a better enrichment. The remaining data seem adequate and will be analyzed in the next few weeks.

Further experiments planned are $Te^{120}(d,p)Te^{121}$ and $Te^{123}(d,p)Te^{124}$ using targets that are to be prepared from partially enriched material in the isotope separator in Aarhus, Denmark. (W. H. Moore and A. Graue)

1. A. Graue, E. Jastad, J. R. Lien, P. Torvund, and W. G. Moore, Nuclear Phys., to be published.
2. W. H. Moore, G. K. Schlegel, S. O'Dell, A. Graue, and J. R. Lien, Nuclear Phys., to be published.

XII. The $Ba^{138}(d,p)Ba^{139}$ Reaction

A 99.8 % enriched Ba^{138} target was bombarded with 7.5 MeV deuterons, and the proton angular distributions were measured using the multiple-gap spectrograph. This experiment will be used to study the energy levels of Ba^{139} up to 3.5 MeV excitation energy, and to complete the previous study of this reaction done with a natural barium target. (J. Rapaport)

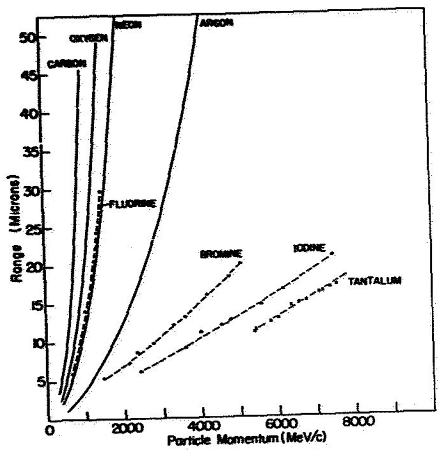
XIII. Range-Energy Measurements for Heavy Ions in Nuclear Emulsions

With the prospects in the near future of obtaining monatomic and monoenergetic streams of particles with very high energies, the nuclear emulsion technique will become more useful as a tool, both for registering and measuring the nuclear events following interactions between complex nuclei. This is particularly so in those cases where the lifetime of the event or the probability of occurance is very, very small. The energy-loss mechanism of heavy ions passing through matter is not very well known and the available experimental data is limited both to specific atomic species and energy range. A more complete study of the response of different nuclear emulsions to the passage of heavy ions of different specie and energy would thus be most useful in interpreting events resulting from nuclear interactions.

With the availability of the MP Tandem facility at the High Voltage Engineering Corporation in Burlington about a year ago, we were given an opportunity at the invitation of the late Dr. R. J. Van de Graaff to participate in obtaining range-energy measurements in nuclear emulsions for different atomic species. Both magnetic and electrostatic analyzers were used to select ion components of specific mass and energy and both Ilford and Eastman Kodak nuclear emulsions were tested.

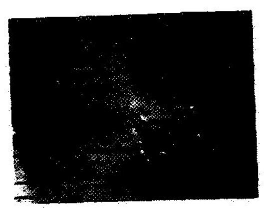
A preliminary report of the range measurements for fluorine, bromine, iodine, and tantalum was presented at the American Physical Society meeting in January.[1] A more complete report for publication is in preparation. Fig. 5.16 shows some results of the present measurements along with those of lighter ions obtained by Heckman, et al.,[2] from the Berkeley HILAC. In Fig. 5.17 are shown two microphotographs of tracks formed by fluorine and uranium ions. (J. W. Reynolds, A. Sperduto, and W. W. Buechner)

1. A. Sperduto, W. W. Buechner and R. J. Van de Graaff, Bull. Am. Phys. Soc. 12, 28 (1967).
2. H. H. Heckman, B. Parkins, W. Simon, F. Smith and W. Barkas, Phys. Rev. 117, 544 (1960).

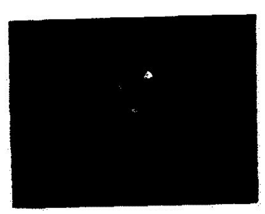


RANGE VS MOMENTUM IN NUCLEAR EMULSION

Fig. 5.16



Tracks of fluorine ions with ranges up to 50 microns (~100 MeV). Note direct straight-line paths with only occasional slight curvature near end of range.



Tracks of mostly uranium ions (~200 MeV). Note frequent collisions with atomic nuclei in emulsion. The longer tracks probably result from uranium ions colliding with the lighter emulsion constituents such as H, C, N, and O. The shorter branches are probably from collisions with bromine and silver.

Fig. 5.17

XIV. A Carbon Polarimeter for Analogue State Spin Measurements

A polarimeter has been designed and built for use in proton elastic and inelastic scattering from analogue state resonances to measure nuclear spin.[1] The device makes use of a thick carbon foil as the second scatter and two $\Delta E/E$ telescopes placed at 46° to each side of the first scattering direction. Solid state counters of one inch diameter will be used in the telescope. Ultra precision machining of the slit and counter tubes was used to reduce spurious instrumental asymmetries in the second scattering. The instrument was designed to be mounted either in the new scattering chamber or on the focal plane of the existing magnetic spectrographs. (E. R. Cosman)

XV. Reconstruction of Beam Pipe Assembly

A reconstruction of the magnetic analyzer beam pipe assembly is presently under way. This has involved new slits, valves, viewers, and vacuum cavities. The machining of analyzer vacuum box is now completed and the commercial slits, valves, viewers, bellows, and other hardware have been delivered. The purpose is to allow quicker and more accurate alignment of the entire beam system and to permit easy rotation of the ONR 90°-magnetic analyzer for the creation of new beam lines, which is presently extremely difficult. Our specific objective is to make the system completely compatible with the new scattering chamber, a new beam line for Li(Ge) γ-ray detection apparatus, and the future wide-gap and split-pole magnetic spectrographs now being designed. (E. R. Cosman, M. K. Salomaa, and D. W. Baker, Jr.)

XVI. Scattering Chamber

The machining on the multiple purpose scattering chamber has been completed and the assembly and testing is now under way. (T. A. Belote and D. W. Baker, Jr.)

XVII. New High-Precision Spectrograph

Construction has started on a new broad-range spectrograph of the split-pole type.[2] This instrument will have pole pieces of a 50-50 Ni-Fe material for high field reproducibility. Minimum aberration will be attained by use of carefully contoured pole boundaries. In order to

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1. G. Terrel, C. F. Moore, J. L. Adams, and D. Robson, "Isobaric Spin in Nuclear Physics", p. 343, Academic Press (1966).
2. J. E. Spencer and H. A. Enge, Nucl. Instr. and Meth. 49, 181 (1967).

minimize the effect of the spot size on the resolving power, a relatively long (4 meters) object distance is used, thereby minimizing the magnification. The instrument will be mounted initially so as to view the target in the multiple-gap spectrograph. Simultaneous exposures can therefore be made. The deflecting power of the instrument is such that is can later be used for particles of much higher energies than those produced at the ONR Generator facility. (H. A. Enge, D. W. Baker, Jr., and H. J. Iuzzolino)

XVIII. The $Cu^{63}(p,p'\gamma)Cu^{63}$ and $Cu^{65}(p,p'\gamma)Cu^{65}$ Reactions

The gamma-ray de-excitation of the first five excited states of Cu^{63} and Cu^{65} was studied by means of the $Cu^{63,65}(p,p'\gamma)Cu^{63,65}$ reactions. Thin film targets of Cu^{63} and Cu^{65}, respectively, were bombarded by a 6.5-MeV proton beam from the MIT-ONR Van de Graaff generator. A gamma spectrum for each level was obtained in coincidence with protons of the right energy, as determined by the high-intensity magnetic spectrometer elsewhere described in this report. Measured relative intensities of the de-excitation gamma rays were not corrected for angular correlation effects. The experimental results provide evidence for a spin assignment of $5/2^-$ to the 1412-keV fourth excited level of Cu^{63} and the 1623-keV fourth excited level of Cu^{65}. A striking overall similarity in the decay schemes of the two nuclei was observed. (D. L. Smith, Helen Young, and H. A. Enge)

XIX. Particle-Gamma Coincidence Work

A coincidence spectrometer consisting of a high-intensity magnetic spectrometer and a NaI scintillation spectrometer has been designed, tested, and used for $(p,p'\gamma)$ studies. The particle spectrometer consisted of a single magnetic quadrupole lens and the wide ($1\frac{1}{2}$ ") gap at 45 degrees in the multiple-gap spectrograph.[1] The instrument has a solid angle of 32 millisteradians with a measured resolving power[2] of $E/\Delta E = 920$. A novel feature of the instrument is that correction for Doppler broadening (kinematic broadening) is attained by a small rotation of the quadrupole lens about its axis.

The results of the $(p,p'\gamma)$ studies can be found elsewhere in this report. (D. L. Smith, M. N. Rao, and H. A. Enge)

1. D. L. Smith and H. A. Enge, "A Large Transmission, Magnetic, Heavy-particle Spectrometer with Good Resolving Power", MIT-LNS Report No. MIT-2098-276, October 1966.
2. D. L. Smith and H. A. Enge, Nucl. Instr. and Meth. 51, 169 (1967).

XX. New High-Intensity Spectrometer

In order to continue the work on particle-gamma coincidences and to initiate other particle work requiring high intensity and high resolution, we are now converting the single-gap, broad-range spectrograph into a high-intensity instrument. It will be a self-contained system, independent of the multiple-gap spectrograph, and it is intended to complement the multiple-gap spectrograph by allowing for more detailed studies of individual levels. We have increased the gap width from 1/2" to 3/2" by machining off some of the surfaces of the pole pieces and have designed mounts for the same quadrupole as used earlier in the multiple-gap spectrograph. New coils and a power supply (also compatible with the new split-pole spectrograph) have been ordered. To minimize saturation effects, the edges of the pole pieces are being contoured.

For the particle-gamma coincidence work, the electronics planned will provide a complete fast-slow coincidence system capable of handling 0.1 MHz. The storage capacity is 1024 channels and expandable. Solid-state detectors will be used in both channels. An energy resolution of ~ 0.1 percent is expected in both particle and gamma channels with a coincidence resolving time of about 10 to 20 nsec. (J. E. Spencer, T. J. Fitzgerald, and H. A. Enge)

XXI. Automatic Track Scanner (CYCLOPS)

The scanner has proved adequate when used on emulsions selected for good track-grain density and low fog for number densities up to 400 tracks per half mm. Currently, we are working on the signal-handling circuits to extend the range of acceptable number densities and particle-emulsion combinations. We also plan to add an absolute-position indicator to the system. (W. H. Moore, K. Richard, and H. A. Enge)

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ONR Generator Group

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RADIOACTIVITY GROUP

I. Introduction

The continuing programs of the Radioactivity Group fall into three categories. First, investigations of perturbed angular correlations of Coulomb excited gamma rays. This technique, which we have called IMPACT, has been pursued vigorously in a collaborative effort with physicists at the University of Wisconsin; it is now being pursued as well in a collaborative effort with scientists at the MP Tandem Accelerator at Yale. The work at Wisconsin has resulted in a number of completed studies during the past year. The magnetic moments of first 2+ states of mercury isotopes and of platinum isotopes have been measured. Extensive investigations have been carried out on internal fields at nuclei of various solutes in iron, nickel, cobalt, and, most significantly, in gadolinium. The extensive work using IMPACT has led to the discovery of an induced polarization of heavy ions which traverse polarized ferromagnetic domains. This new phenomenon results in a transient positive field and appears to be the result of the pickup by the ion of polarized electrons from the host. An extension of the work at Wisconsin is now in full swing at Yale University. An 80-100 MeV sulphur beam is being used for the studies of perturbed angular correlations of higher excited states than can be reached with the oxygen projectiles of the Wisconsin tandem. A brief summary of this work is contained here.

A second phase of the work is the investigation of internal fields using radioactive sources. A first study of the internal fields in Type II superconductors has been completed. Magnetic moments of various states in samarium, gadolinium and lead have been obtained. Investigations of internal fields on cerium nuclei in ferromagnetic hosts has begun.

The third continuing effort is the work on isomer shifts using the Mössbauer effect. This year we have succeeded in measuring the change in charge radius between members of the rotational band in Eu^{153} as well as several even-even nuclei, and a summary of this work is included.

An experiment on the perturbed angular distribution of resonantly scattered radiation has terminated. The results are included here, even though they leave a number of questions unanswered.

Two new projects, which are allied to the above investigations, have been begun this year. The first of these projects is a collaborative effort with the Cyclotron Group to use nuclear reactions to measure magnetic moments using the IMPACT technique. This work has resulted in one completed experiment, described below, on Fe^{56}. The technique is being vigorously pursued to measure g factors of other states in ferromagnetic materials. A second project concerns the use of perturbed angular correlations for the measurements of states fed by alpha particle decay. Previous attempts at such measurements, carried out both in this and in other laboratories were unsuccessful due to the lack of knowledge of the solid state phenomena involved. We believe that we now understand the phenomena sufficiently so that we have a fair chance of successfully measuring a number of magnetic moments using a modified form of the IMPACT technique.

During the past year, a considerable effort of the group was devoted to the TU Van de Graaff proposal. Some of the experimental results on stripping and energy loss of heavy ions in foils and gas are summarized below. Of particular concern to the group were heavy ion interactions which could lead to the formation of transuranic elements. These studies are continuing, the emphasis being on the use of a proposed MP-XTU facility to be located at Burlington, Massachusetts. This work is not described in this progress report, but it is expected that the feasibility studies will continue through the year and will occupy a fair fraction of the time of the group.

II. Ion Implantation Perturbed Angular Correlation Technique (IMPACT)

A. Magnetic Moments of the First Excited 2+ States in the Even Pt Isotopes[1]

Integral precession measurements for the first excited 2+ states in Pt^{194}, Pt^{196} and Pt^{198} were measured. The levels were Coulomb excited by backscattered oxygen ions from the University of Wisconsin tandem accelerator with the excited nuclei recoiling into a polarized iron backing. By combining the measured values of $\omega\tau$ for Pt^{194} with earlier radioactivity results, one gets for the effective internal magnetic field acting on the Pt nuclei implanted in iron $H_{int}(\text{recoil}) = (-0.89 \pm 0.07) \times 10^6$ Gauss. The g factors for Pt^{194}, Pt^{196} and Pt^{198}, deduced from the measured precession angles and from the above value of the internal field are given in Table 6.I. A comparison of the experimentally determined g factors with the theoretical predictions of Kumar and Baranger[2] and of Greiner[3] is also given in Table 6.I. The agreement between both theories and the experimental results is good. (L. Grodzins and R. Kalish)

1. R. Kalish, L. Grodzins, R.R. Borchers, J.D. Bronson and B. Herskind, "Magnetic Moments of the First Excited 2+ States in the Even Pt Isotopes", Phys. Rev. 161, 1196 (1967).
2. K. Kumar and M. Baranger, Phys. Rev. Letters 17, 1146 (1966), and private communication.
3. W. Greiner, Nucl. Phys. 80, 417 (1966).

Table 6.I

Nucleus	$E_{keV}(2+)$	$\tau_{psec}(2+)$	Kumar et al.[1]	Greiner[2]	g Experiment
Pt^{194}	328.5	51 ± 4	0.293	0.307	0.32 + 0.04
Pt^{196}	355.7	47.4 ± 5	0.301	0.303	0.27 ± 0.04
Pt^{198}	408	25.5 ± 3	—	0.299	0.28 ± 0.04
			Kumar et al.[1]	Covello[3]	
Hg^{198}	411.8	31.8 ± 1.5	0.465	0.605	0.55 ± 0.11
Hg^{200}	367.9	67.2 ± 20.7	0.421	0.610	0.73 ± 0.27
Hg^{202}	440	35.3 ± 7.3	0.255	—	0.77 ± 0.23
Hg^{204}	430	13.3 ± 6.6	0.264	—	0.29 ± 0.15

B. Magnetic Moments of the First Excited 2+ States in Even Hg Isotopes[4]

The Larmor precession angles of the first 2+ states of Hg^{198}, Hg^{200}, Hg^{202} and Hg^{204} implanted in polarized iron have been measured. A 33 keV oxygen beam from the University of Wisconsin Tandem accelerator was used to excite and implant the mercury nuclei. The effective magnetic hyperfine field acting on Hg^{198} was found to be a factor of two smaller than the effective field observed using radioactive sources. The present results for the g factors of Hg^{200}, Hg^{202} and Hg^{204}, normalized to the known g value of the 2+ state in Hg^{198}, as measured in an external magnetic field, are given and compared with theoretical predictions in Table 6.I. The g values for the 2+ states of Hg^{198} and Hg^{200} are greater than Z/A, in accord with the predictions of Kumar[1] and Covello.[3] The sharp decline in the g values predicted by Kumar to occur between Hg^{200} and Hg^{202} is not observed, but a large decrease in the magnetic moment seems to occur between Hg^{202} and Hg^{204}. (L. Grodzins and R. Kalish)

1. K. Kumar and M. Baranger, Phys. Rev. Letters 17, 1146 (1966), and private communication.
2. W. Greiner, Nucl. Phys. 80, 417 (1966).
3. A. Covello, private communication.
4. R. Kalish, L. Grodzins, D. Murnick, R.R. Borchers, B. Herskind, J.D. Bronson, "Magnetic Moments of the first excited 2+ States in Even Hg Isotopes", International Conference on Hyperfine Interactions, Asilomar, California, 1967.

C. Internal Magnetic Fields at Mo, Ru, Pd, Sm and Pt Nuclei Implanted in Fe, Co, Ni and Gd Metals[1]

The ion implantation perturved angular correlation technique has been used to determine internal magnetic fields at Mo, Ru, Pd, Sm and Pt implanted into ferromagnetic hosts. The first 2+ states of isotopes of known magnetic moments have been Coulomb excited by back-scattered oxygen ions from the University of Wisconsin tandem. The values and signs of the internal fields acting on the ions implanted in Fe, Co, Ni and Gd (cooled to $80^{\circ}K$) have been deduced from the measured precession angles. The ratios $H_{Fe}(X) : H_{Co}(X) : H_{Ni}(X)$ agree well with values measured by other techniques and are approximately proportional to the magnetic moments of the host atoms (see Figure 6.1). The absolute values of the internal fields, though, deviate from the values measured by other techniques. It is, therefore, concluded that the anomalous fields observed using high recoil IMPACT[2] are proportional to the atomic moment of the host.

Values for $H_X(Gd)$, have been measured for Mo, Ru, Pd, Sm and Pt. There are however not enough data of internal fields acting on impurities in Gd to answer the vital question of whether anomalous fields are encountered using Gd as a host in high recoil IMPACT. The present indications are that, if present, such anomalies are small.

Further measurements of internal fields in ferromagnetic hosts, especially Gd, are in progress. If Gd proves to be a host in which no anomalies in the internal fields are observed, even for high recoil implantation, then it will be the ideal backing for measurements of magnetic moments of excited states using the IMPACT methods. (L. Grodzins and R. Kalish)

D. Anomalous Hyperfine Fields in Fe Hosts[2,3]

IMPACT measurements on the first 2+ states of $Se^{76,78}$, $Mo^{98,100}$, $Ru^{98,100,102,104}$, $Pd^{104,106,108,110}$, $Cd^{110,112,114,116}$, $Te^{120,122,124,126,128}$, $Pt^{194,196,198}$ and $Hg^{198,200,202,204}$ were carried out in collaboration with scientists at the University of Wisconsin, using an oxygen beam from their EN Tandem. A comparison of the $\omega\tau$ values obtained by IMPACT to the corresponding results obtained by embedding radioactive sources in iron is given in Figure 6.2. Not a single IMPACT result is in accord with a static measurement; there seems to be a consistent anomalous field acting on the fact recoiling implanted

1. D. Murnick, L. Grodzins, R. Kalish, R.R. Borchers, J.D. Bronson, B. Kerskind, International Conference on Hyperfine Interactions, Asilomar, California, 1967.
2. L. Grodzins, International Conference on Hyperfine Interactions, Asilomar, California 1967.
3. B. Herskind, R.R. Borchers, J.D. Bronson, D. Murnick, L. Grodzins, and L. Kalish, International Conference on Hyperfine Interactions, Asilomar, California, 1967.

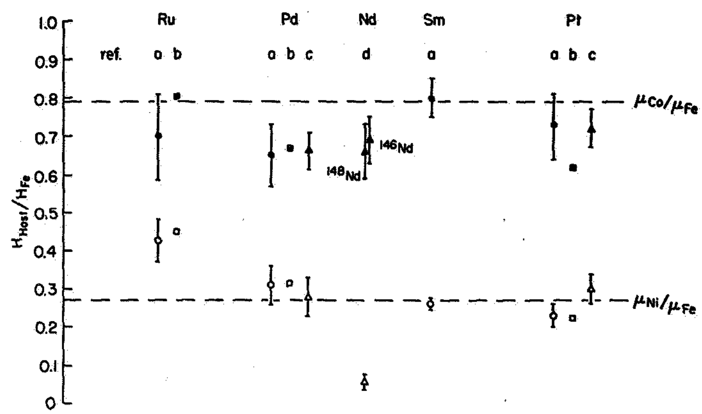

Figure 6.1

Ratio of internal fields at solute ions in hosts of cobalt and nickel normalized to the internal field observed in iron. Refs. a and d refer to IMPACT work, Ref. b refers to nuclear magnetic resonance results, and Ref. c refers to perturbed and correlation results.

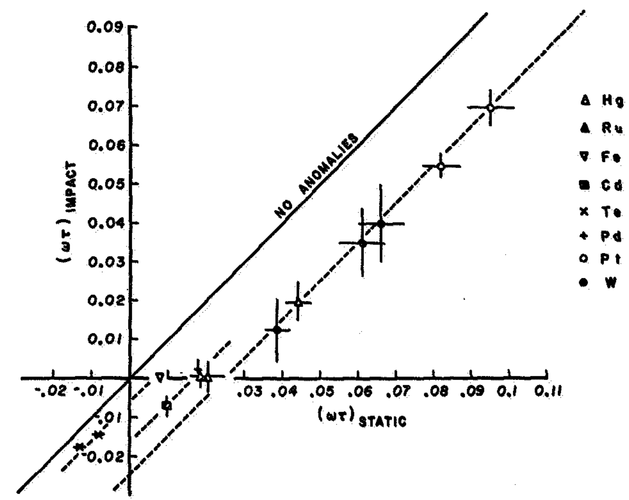

Figure 6.2

IMPACT versus static values of $\omega\tau$. The tungsten values are for 4+ states; $(\omega\tau)_{STATIC}$ are calculated assuming $g_{4+} = g_{2+}$.

nuclei. By observing the $\omega\tau$ values for 2+ states of different isotopes of the same atom, one may get an idea about the time dependence of this anomalous field. This is illustrated in Figure 6.3, where $\omega\tau_{IMPACT}$ is plotted versus τ for the first 2+ states of the Te, Ru and Pd isotopes. The $\omega\tau$ values for a given element fall on a straight line which does not extrapolate to $(\omega\tau)_{\tau=0}=0$. The solid lines on the figure are the expected plots of $\omega\tau$ vs τ, assuming the static value of H_{int} and a constant value of g.

The data imply that the nuclei feel a sharp impulse precession due to a positive magnetic field which adds to all measurements of $\omega\tau$.

In order to determine at what stage in the history of the recoiling nucleus the anomaly occurs, runs on "sandwich" targets, in which the recoiling excited nuclei were slowed down in a Cu moderator before reaching the iron, were done. The results of such runs are shown in Figure 6.4. The large anomaly nearly disappears at moderator thicknesses of 800 $\mu g/cm^2$. These results confirm the results of low recoil reaction implantation, where no anomalies could be observed[1].

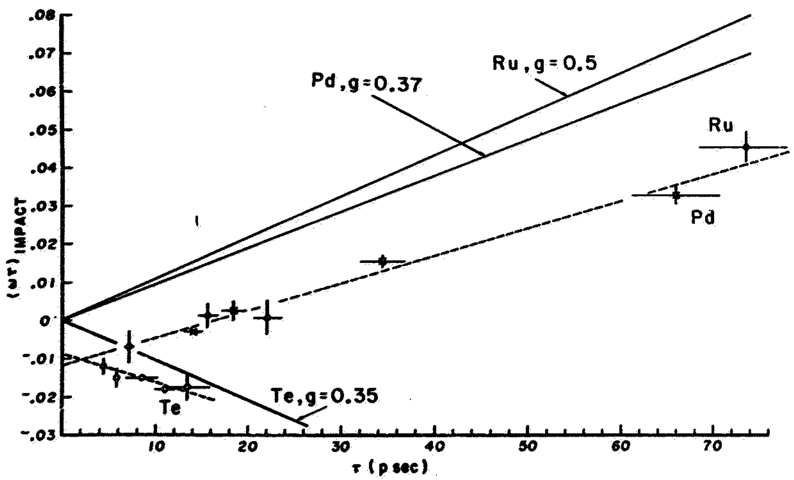

Figure 6.3

$\omega\tau$ versus copper moderator thickness for a) ^{114}Cd-Cu Fe and b) ^{116} Cd-Cu-Fe.

1. R. Kalish and W. J. Kossler, International Conference on Hyperfine Interactions, Asilomar, California, 1967.

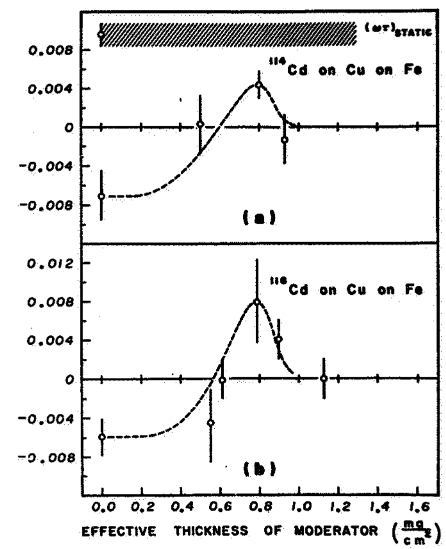

Figure 6.4

Larmor precession angles, obtained with IMPACT, versus τ for 2+ states of Ru, Pd and Te isotopes. The dashed lines are arbitrarily drawn. The solid lines are the expected loci, assuming constant g values for the 2+ states.

It seems as if a transient field with the following properties causes the observed anomalies:

1) A transient positive field, H_1, lasting $\lesssim$ 5 psec, is present on non-rare earth atoms which recoil with MeV energy into Fe, Co or Ni.

2) H_1 is proportional to the atomic moment of the host.

3) H_1 is much reduced (and may be zero) when the initial recoil velocity in the ferromagnetic host is $\lesssim 10^8$ cm/sec.

4) H_1 does not appear to be present on rare earth ions implanted in ferromagnetic backings.

5) The evidence is consistent with a transient field arising from the pick-up of polarized d electrons as the recoiling ion neutralizes in the Fe, Ni or Co lattices.

6) There does not appear to be a strong transient field on ions recoiling into Gd metal.

Table 6.II

Method		$\omega\tau$	$\overline{\omega\tau}_{av.}$	$H_{int}(Fe\text{-}Fe) \times 10^6$ Gauss
Present Experiment	Set 1 Ge(Li)	0.011 ± 0.009	0.0106 ± 0.0021*	-0.43 ± 0.14
	Set 2 NaI(Tl)	0.0085 ± 0.0023		
	Set 3 NaI(Tl)	0.014 ± 0.003		
Radioactivity	γ-γ Precession	0.0079 ± 0.0037	0.0083 ± 0.0020	-0.339
	Resonance Flourescence	0.0085 ± 0.0024		
High Recoil Coulomb Excitation		0.0004 ± 0.0010	0.0004 ± 0.0010	-0.016 ± 0.040

*The error in $(\omega\tau)_{av.}$ includes a 10% uncertainty in the slope of the angular distribution.

7) These transient fields mask anomalies which might be present due to radiation damage, interstitial site position and solute poisoning in the ferromagnetic backings. What little evidence exists indicates that none of these phenomena lead to large anomalies.

The work on the anomalous fields continues in three main directions:

1) Further understanding of the anomalous field: when it occurs and what, exactly, is its mechanism.

2). "Freezing" the transient field, which may provide extremely high hyperfine magnetic fields (5-10 x 10^6 Gauss) which can be used for precession measurements.

3) Searching for a ferromagnetic environment free of anomalous fields which can be used for magnetic moment measurements. The present results seem to indicate that Gd may be such an environment. (L. Grodzins and R. Kalish)

E. Precession Measurements of the 0.847 MeV Level of Fe^{56} Implanted in Iron After a (p, p') Reaction[1]

The IMPACT method has been extended in this work to a level which was populated by a nuclear reaction. The nuclear reaction mechanism, which has never before been used in conjunction with precession measurements of a short lived level in ferromagnetic environments has two advantages: (1) it enables one to reach levels which cannot be reached by radioactivity and Coulomb excitation methods, and (2) no anomalies in the internal fields seem to exist after implantation at low recoil energies, a characteristic of a light particle induced reaction. Thus, magnetic moments of excited states may readily be deduced from the measured precession angles.

A natural iron foil was bombarded with 7.8 MeV protons from the MIT cyclotron. The first excited 2+ level of Fe^{56} at 0.847 MeV (τ = 1.6 psec) was strongly excited by the (p, p') reaction. The precession of the excited iron nuclei, which obtained a recoil energy of less than 400 keV, was measured by observing the precession of the gamma ray angular distribution using Ge(Li) as well as NaI(Tl) detectors. The results of the precession values are compared in Table 6.II with $\omega\tau$ values obtained by other techniques. The values of H_{int}, given in the fourth column of the table, were calculated by use of the relationship

$$H_{int}(\text{recoil}) = \frac{\omega\tau(\text{recoil})}{\omega\tau(\text{static})} H_{int}(\text{static})$$

where $H_{int}(\text{static}) = -0.339 \times 10^6$ Gauss.

1. R. Kalish and W.J. Kossler, International Conference on Hyperfine Interactions, Asilomar, California, 1967.

The value of the internal field fater the low reaction recoil agrees very well with the known static value of the field. The strong anomaly observed in the high recoil experiments is not observed in the present work, indicating that, at least in the Fe-Fe case, the anomaly occurs during the first part of the recoil, when the excited nuclei will move fast ($> 10^8$ cm/sec).

The measurements of magnetic moments of states excited by low recoil nuclear reactions, the feasibility of which has been demonstrated on the Fe^{56} 0.847 MeV level, will continue at the MIT Cyclotron. Several levels in the vicinity of iron are being investigated. (R. Kalish and J. W. Kossler)

F. IMPACT Measurements Using the MP Tandem Accelerator at Yale

Higher excited states than the first 2+ states of even nuclei can be reached by Coulomb excitation with heavy energetic ions. Such beams of heavy (A = 32) energetic (E ~ 80 MeV) particles are produced by the MP tandem accelerator at Yale University.

In a collaborative effort with Yale, we have set up the equipment for IMPACT measurements. The first measurements are being carried out on higher excited states in the even Os isotopes. In Os^{192} we observe the precession of at least 3 levels: the first 2+ level at 108 keV (the g factor of which is still uncertain, due to a large discrepancy between the reported values), the second 2+ level at 489 keV, and the 4+ level at 590 keV. (L. Grodzins and R. Kalish)

G. IMPACT Using α-Decay

An experiment has been assembled to measure α-γ angular correlations perturbed by internal fields of the α-recoil environment. This is a variation of the IMPACT type measurements, in which the excitation and implantation are obtained as a consequence of the α-decay. With the advantages of low implantation energies (as compared to those obtained in Coulomb excitation), this technique opens up a great number of possibilities for studying the levels populated by α-decay in heavy elements and has the advantage over IMPACT via Coulomb excitation that the recoil energies are low. Considerable progress in this experiment is expected during the coming year. (L. Grodzins, R. Kalish and E. Ansaldo)

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1. L. Grodzins, International Conference on Hyperfine Interactions, Asilomar, California, 1967.
2. B. Herskind, R.R. Borchers, J.D. Bronson, D. Murnick, L. Grodzins, and L. Kalish, International Conference on Hyperfine Interactions, Asilomar, California, 1967.

III. Charge Exchange and Stopping Power of Heavy Ions in Gases and Goils

A. The Stripping of Electrons from Fast Moving Br, I, Ta and U Ions in Thin Carbon Foils

X

The charge stripping of fast (25-185 MeV) moving Br, I, Ta and U ions passing through carbon foils were measured last summer (June-September, 1966) in a collaborative effort with scientists from High Voltage Engineering Corporation using their experimental MP tandem facilities.[1] These data were analyzed carefully, yielding information not only about the most probable charges at equilibrium, but about the complete charge distributions as well.

The most probably charges at equilibrium, determined in the present measurement, are in good agreement with values reported by other groups, taken at lower energies. The values of $\bar{Q}$ seem to deviate with increasing energy from any simple $E^{1/2}$ dependence. The experimental data also deviate somewhat at high energies from the empirical expression $\bar{Q}/Z = 1 - C\exp(-D(E^{1/2}))$ proposed to fit the values of $\bar{Q}$ for lower energies. (C and D are numerical constants.)

The widths of the charge distributions, γ, were measured at $\frac{1}{e}$, 20% and 10% of the maximum of the distribution curve. The results for Br and I are plotted in Fig. 6.5. As can be seen from that figure, there are no large deviations in γ over a wide range of energies, being roughly 2 for Br as well as for I. The small deviations observed indicate the effect of the atomic shells, the minima of the curves occurring just before new shells (L shell for Br and μ shell for I) have to be broken up. (L. Grodzins, R. Kalish and F.M. Flasar)

B. The Cross Section for Electron Charge Exchange of Br Ions in Hydrogen

The charge distributions of Br ions traversing through a hydrogen gas cell at various pressures were measured last summer, using the experimental MP tanden facilities at High Voltage Engineering Corp. The data taken for 45.5 MeV Br ions with initial charge states +11 and +10 and hydrogen pressures ranging from 750-25,000 micron-cm were analyzed. Assuming only single electrons stripping or pickup, one can write the following coupled differential equation to describe the change in charge state:

$$\frac{dF(I)}{dn} = F(I+1)S(I+1,I) + F(I-1)S(I-1) - F(I)\left[S(I,I+1) + S(I,I-1)\right]$$

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1. L. Grodzins, R. Kalish, D. Murnick, R.J. Van de Graaff, F. Chmara and P.H. Rose, Phys. Letters 24B 282 (1967).

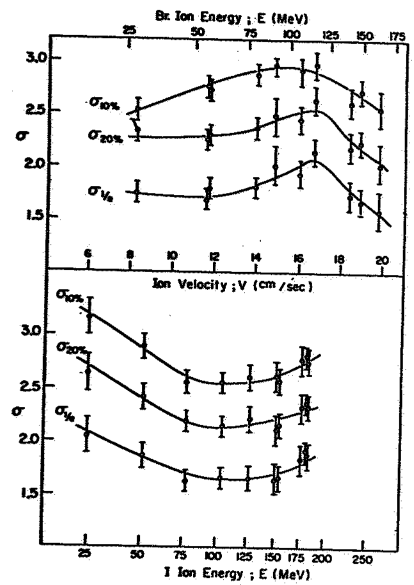

Figure 6.5

where

M = Number of atoms/cm^2

$F(I)$ = Fraction of beam in charge state I

$S(IJ)$ = Cross section for charge exchange from charge I to J

This set of differential equations was solved by a computer. The results are presented in Figures 6.6 and 6.7, the electron capture cross section $S(I, I-1)$, as obtained from the solution of the above equations, is plotted in Figure 6.6 for the various initial charge states I. The anomalously low cross section for I=9 shell is due to the transition from the fitted $3d^8$ to the $3d^8 4s^1$ states. The pressure dependence of the charge distribution as calculated with these cross sections, is compared with the experimental distribution in Figure 6.7. The reasonable good fit obtained indicates that the simple model assumed in the present analysis is a fairly good description of the charge exchange process. (L. Grodzins, R. Kalish and J.H. Udinsky)

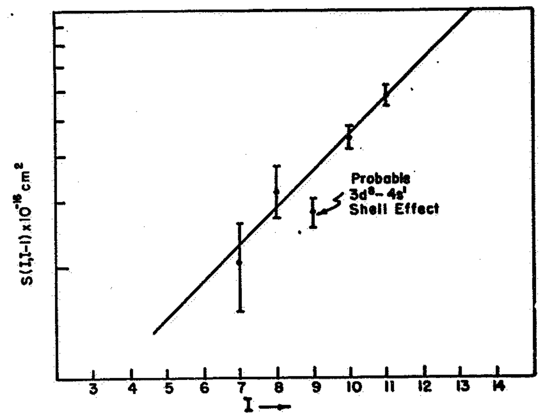

Figure 6.6

Capture cross section vs. initial charge state

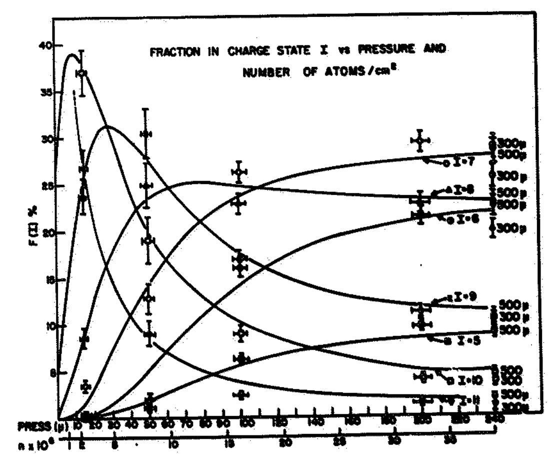

Figure 6.7

Fraction in charge state I vs. pressure and number of atoms/cm^2

C. Stopping Power of 13-100-MeV Ta Ions in Various Foils. [1]

A tantalum beam was accelerated in the High Voltage Engineering Corporation experimental M.P. tandem and was passed through C, Fe, Al, Ni, Ag, Au, and UO_2 foils of thicknesses up to 400 $\mu g/cm^2$. The energy loss of the tantalum ions, due to their passage through foils, was deduced from the shift of the energy spectra (as recorded in a calibrated heavy ion solid state detector) with and without a foil in the way of the beam. Some of the dE/dx data are presented in Fig. 6.8. (L. Grodzins, R. Kalish, F. Flaser, J. Udinsky, in collaboration with P.H. Rose, F. Chmara, High Voltage Engineering Corporation, Burlington, Mass.)

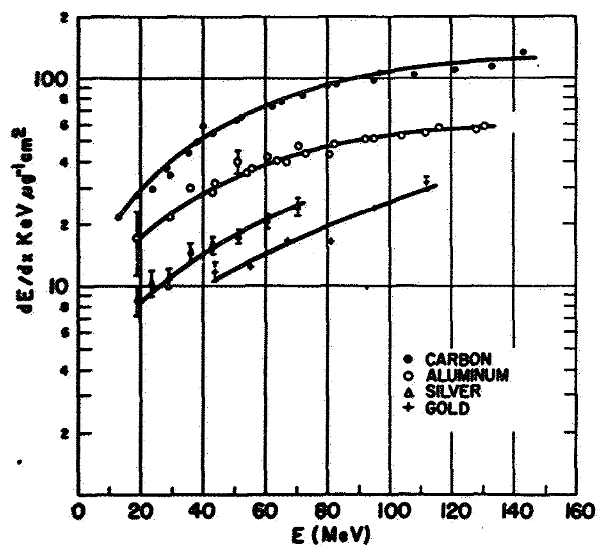

Figure 6.8

1. P.H. Rose, F. Chmara, L. Grodzins, and R. Kalish, "Stopping Power of 13-100 MeV Ta Ions in Various Foils," Bull. Am. Phys. Soc., Series II, Vol. 12, No. 4, 476 (1967).

IV. Perturbed Angular Correlation Using Radioactive Sources

Perturbed Angular Correlation of gamma-gamma cascades has been used to study internal magnetic fields at dilute impurities in iron and to measure the g-factors of short-lived excited states of nuclei using these internal fields. Temperature dependence of internal magnetic fields have been studied in some cases. The results are given below.

g-factor measurements

Nucleus	Energy	Spin parity	Meanlife	H_{int}	g-factor
Pb^{208}	2615 keV	3^-	47 ps	262 kG	+0.08 $\pm$ 0.07
Pb^{208}	3198 keV	5^-	.43 ns	262 kG	+0.057 $\pm$ 0.008
Os^{192}	206 keV	2^+	.393 ns	1110 kG	+0.19 $\pm$ 0.02
Gd^{152}	344 keV	2^+	76 ps	-152 kG	+0.40 $\pm$ 0.07

Internal Magnetic fields

Nucleus	Energy	Spin parity	Meanlife	g-factor	H_{int}
Pb^{207}	570 keV	$5/2^-$	110 ps	+ 0.34	+262 $\pm$ 20 kG
Sm^{152}	367 keV	4^+	.12 ns	+ 0.32	+1.16 $\pm$ 0.10 MG
Gd^{154}	371 keV	4^+	56 ps	+ 0.367	-152 $\pm$ 40 kG

Temperature dependence

In Sm and Gd the internal magnetic fields have been measured at room temperature, liquid nitrogen temperature and liquid helium temperatures. The ratio of the fields are

Sm 1 : 1.3 : 1.05

Gd 1 : 1.1 : 0.5

In Osmium the temperature dependence of magnetization has been measured from liquid helium to above the Curie temperature of iron. The magnetization curve approximately follows that of iron.

The experimental results are interpreted in terms of current theories of nuclear structure and solid state physics.

Radioactive sources for these studies have been prepared by electroplating, alloying and ion-implantation techniques.

Preliminary measurements have been made on the magnitude and sign of the internal fields acting on the Ce^{140} nucleus in iron and nickel foils. The measurements were made by determining the Larmor precession angle in the 329-487 angular correlation in Ce^{140}. Two sources have been prepared by isotope separator implantation of La^{140} at 60 kilovolts; this work was done in collaboration with Prof. R. Naumann of Princeton University. As yet no effect has been seen with Ce^{140} in iron foil.

Definite precession was observed in nickel. Measurements at room temperature and also near the Curie temperature of nickel have not yet yielded consistent values for the magnitude of the internal field. It appears however that the sign of the field is negative, contrary to theoretical expectations.

V. The Mössbauer Effect

A. Isomer Shift of Even-Even Deformed Nuclei

Isomer shifts in low lying states of deformed nuclei. The work on isomer shifts whose preliminary results were given in the 1965 LNS Physics Progress Report has been completed. The following is the abstract of the thesis submitted to the Physics Department by David Yeboah-Amankwa for the Ph.D. degree on January 1967.

A very stable and linear Mössbauer spectrometer has been built and used in the absorption type experiment as liquid helium temperature to study the isomer shifts between the first excited 2+ and the o+ ground states of Sm^{152}, Gd^{154}, Gd^{156}, W^{184} and W^{186}. The Mössbauer lines are 122, 123, 89, 111 and 123 keV respectively. In the Gd^{154} and Sm^{152}, this represents the first observation of the Mössbauer effect in those isotopes. The results obtained follow in the table below. The $\Delta\langle R^2\rangle/R^2$ is given where electronic wavefunctions are available.

Isotope	Source	Absorber	Isomer Shift in mm/sec	$\frac{\Delta\langle R^2\rangle}{R^2}$ in 10^{-4}
Sm^{152}	Eu^{152}	SM_2O_3	1.65 ± 0.15	6 ± 2
Gd^{154}	Eu^{154} in CaF_2	Gd_2O_3	0.16 ± 0.07	—
Gd^{156}	$Eu_2^{156}O_3$ in Sm_2O_3	Gd-metal	0.26 ± 0.09	0.6 ± 0.2
W^{184}	Re^{184} in Cu	WCl_6	-0.171 ± 0.04	
W^{186}	$Re_2^{186}O_3$	W-metal	0.14 ± 0.1	—

The really significant results are on Sm^{152} and the ratio for W^{184} and W^{182}. In Sm^{152}, the $\Delta\langle R^2\rangle/R^2$ is much less than that expected from the calculations using energy deviations from the I(I+1) rotational rule; it is also less than expected from β-band mixing. It thus appears that the mechanism which causes the energy level depressions do not produce large changes in the nuclear charge distribution.

The W^{184} is compared with an identical measurement on W^{182}. Contrary to theoretical results, the W^{184} is observed to have a smaller $\Delta\langle R^2\rangle/R^2$ than the value for W^{182}.

$$\left[\Delta\langle R^2\rangle/R_2\right]_{W^{182}} \Big/ \left[\Delta\langle R^2\rangle/R^2\right]_{W^{184}} = 1.6 \pm 0.4.$$

The hyperfine interaction of the 3^+ ion of Sm^{152} in CaF_2 was measured to be equivalent to 3.7 ± 0.4 MG at the nucleus, in agreement with the theoretically calculated value of the free ion field due to the 3^+ Sm ion.

B. Isomer Shift of the 83 keV First Excited State in Eu^{153}

The Mössbauer absorption effect has been observed on the 83.4 keV interband transition between the first excited state and the ground state in Eu^{153}. This is therefore the third level in Eu^{153} to be investigated with the Mössbauer technique, extensive measurements having been made on the intra band transitions from the 97 keV and 103 keV levels. The present study was undertaken in order to determine the isomer shift of the 83.4 keV state and thus the centrifugal stretching in the rotational band. The two main experimental difficulties in the detection of the 83.4 keV ray are: 1) its proximity in energy to the other levels, which was overcome by the use of solid state detectors, and 2) its low relative intensity. The ratio of intensities of the three lines being:

I(83.4):I(97.4):I(103) = 0.18:0.58:28 in the Sm^{153} decay, and
0.23:30:20 in the Gd^{153} decay

The Sm^{153} (47 hrs.) decay was chosen as a parent, because of the intrinsic low intensity of the 97 keV ray and the relative intensity of the 83.4 keV level was enhanced by the use of an 0.016" Pb critical absorbers.

A series of transmission measurements were then taken at liquid He temperature. The source was in the form of Sm_2O_3, obtained by neutron irradiation of Sm_2O_3, in the M=I=T=reactor.

The transmission spectrum for an Eu_2O_3 absorber is shown in Fig. 6.8, gating first on the 103 keV and then on the 83.4 keV lines, for which the measured F.W.H.M's are 1.7 mm sec^{-1} and 5.0 mm sec^{-1} respectively. Using a thin absorber, a F.W.H.M. of 3.5 mm sec^{-1} expected from the measured mean life of 1.09×10^{-9} sec.

Isomer shifts were observed for absorbers of EuB_6 and $EuSO_4$ (Eu^{2+}) relative to the source of $Sm_2O_3(Eu^{3+})$ (Fig. 6.9). Studies of the 21.7 keV transition in Eu^{151} and both the 97 and 103 keV transitions in Eu^{153} have shown that Eu in $SuSO_4$ has the smallest $|\Psi_s(0)|^2$ of all divalent compounds, and hence the largest isomer shift. The shifts observed are:

	EuB_6	$EuSO_4$
83.4 keV	+ .52 ± .15 mm/sec	+ .80 ± .20 mm/sec
103 keV	+16.32 ± .15 mm/sec	+17.53 ± .15 mm/sec

The results for the 103 keV line are in close agreement with previous work. The positive sign in the 83.4 isomer shift (in the same direction as the shift of the 103 keV line) means that the 83.4 keV first excited state has a negative $\frac{\Delta\langle R^2\rangle}{R^2}$ relative to the ground state. Using the calibration scheme proposed by Brix, et al., $\Delta|\Psi(0)|^2 = -1.9 \times 10^{26}$ cm^{-3} we obtain

$$\frac{\Delta\langle R^2\rangle}{R^2} = -1.6 \pm 0.5 \times 10^{-4}$$

A possible explanation of the negative value for the change in nuclear mean square radius can be given within the framework of Nilsson states by the mixing of the K=3/2 band (whose head is the 103 keV level) into the K = 5/2 ground state band via the RPC (coriolis coupling) interaction. Calculations are currently in progress to obtain an estimate of this effect.

A broadened line was observed with an EuO absorber, the broadening being interpreted as unresolved hyperfine structure. Measurements are in progress with a sample of EuIG, in an attempt to resolve the hyperfine structure of the 83 keV level in the 600 Kgauss field existent at the site of the Eu nucleus in that material.

C. Quadrupole Moment Ratios in W^{182}, W^{184}, W^{186}

Work is in progress in Mössbauer transmission experiments on the first (2+) excited states of W^{182} (100 keV), W^{184} (111 keV) and W^{186} (122 keV) with the purpose of obtaining information on the relative quadrupole moments of the states; information of importance for testing nuclear models.

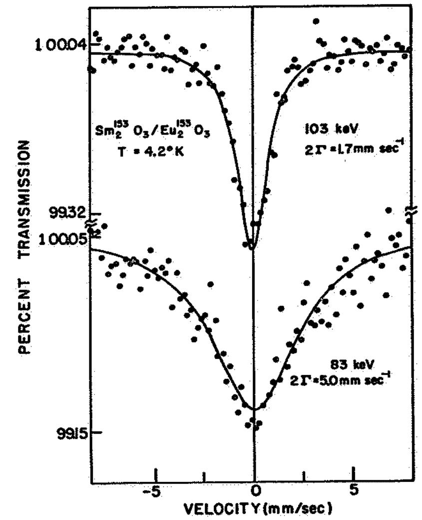

Figure 6.8

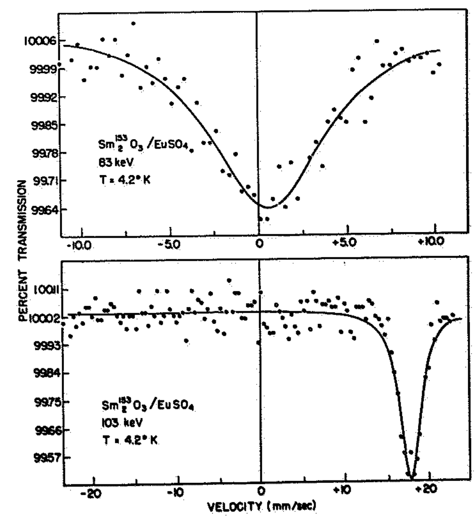

Figure 6.9

Normally the Mössbauer line in non-cubic compounds shows an unresolved structure; the three lines, $\Delta m=2$, 1 and 0 having intensity ratios of 2:2:1 respectively. In this experiment a greater accuracy in the measurement of the splittings is obtained through the use of single crystals. With the c-axis of a single crystal oriented parallel to the direction of propagation of the gamma rays, a single line absorption, from the $\Delta m= \pm 1$ transitions, results. When the c-axis of the crystal is oriented perpendicularly to the gamma ray momentum, two lines of equal intensity are observed arising from $\Delta m = \pm 1$, $\Delta m = \pm 2$ transitions. The quadrupole splitting is then given by the position of the single line, or by the separation between lines, respectively.

Figure 6.10 shows the results obtained for 100 keV, 2+-0+, transition of W^{182} and single crystals of $CaWO_4$. Work is in progress on the W^{184} and W^{186} states.

VI. Internal Magnetic Field Distribution in Type II Superconductors Detected by Perturbed Angular Correlations

The intermediate state magnetic field distribution in superconducting niobium has been studied by means of the time dependent perturbed angular correlation of the 75 keV 84 keV gamma gamma cascade in Rh^{100}. The lifetime and g factor of the 75 keV level in Rh^{100} make it well suited for the study of magnetic fields of a few tens to a few thousand Gauss by the time differential technique. The magnetic field is determined from the precession of the characteristic Larmour frequency of the angular correlation pattern which for this nucleus has a pure $\cos^2\theta$ dependence.

By diffusing the 4 day Pd^{100} parent of Rh^{100} into a niobium lattice in sufficiently low concentrations so as to not affect the superconducting properties of the host, the intermediate state magnetic fields can be measured. The measurements yield, after subtraction of the exponential envelope from the nuclear intermediate state decay, the Fourier inverse of the magnetic field density distribution inside the host lattice. These data can be compared with the distributions calculated on a basis of the Abrikosov model[1] of quantized flux vortices.

Some results are shown in the Figs. 6.11 and 6.12. The first shows a set of data with the pattern expected when the probe nuclei see only the external field. Figure 6.12 shows the same data with the pattern calculated from the quantized fluxoid model. These curves are in no way least squares fits, so the agreement in the latter case is quite meaningful. (The parameters used for the calculations were obtained from bulk susceptibility and resistivity measurements on our samples.)

1. A.A. Abrikosov, Zh. Eksperim. i. Teor. Fiz. 32, 1442 (1957); English Translation in Soviet Physics JETP 5, 1174 (1957).

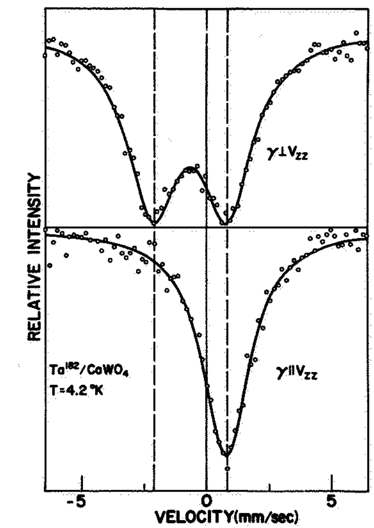

Figure 6.10

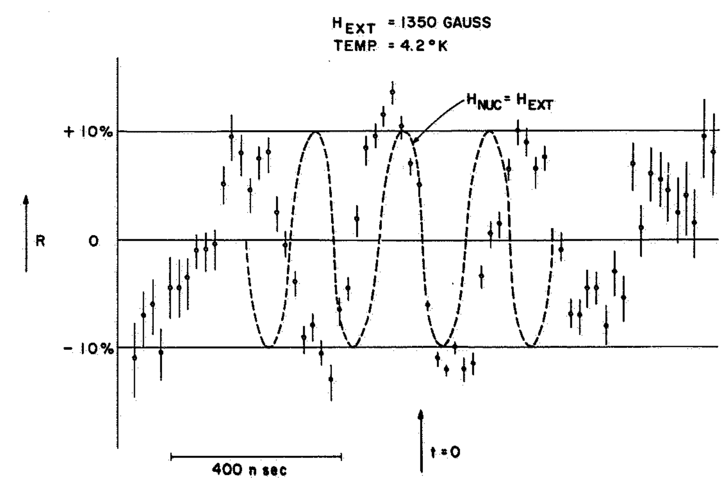

Figure 6.11

Reduced PAC data for Rh^{100} in superconducting niobium, dotted curve shows pattern expected when sample is normal.

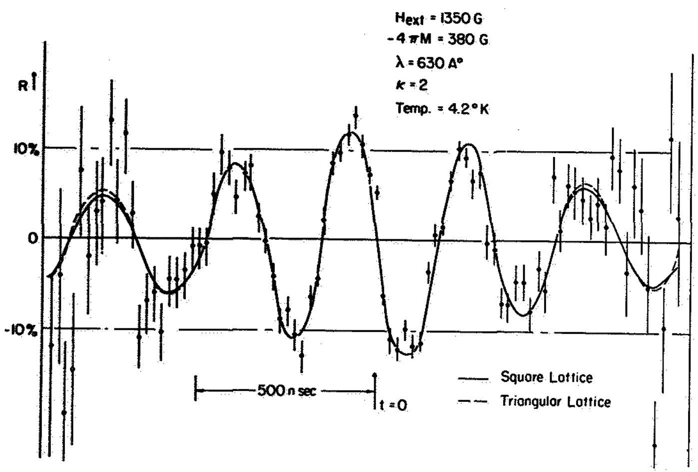

Figure 6.12

Some data as previous figure with dotted curve showing pattern predicted by Abrikosov quantized fluxoid theory.

The good agreement with theory proves that in the mixed state of type II superconductors, magnetic flux is subdivided into single quantized bundles.

It is believed that considerable improvement of the quality of the experimental data is possible, and now that the experiments have been shown to be feasible, efforts along these lines are being made. Three main avenues are being pursued; 1) improved equipment, better time and energy resolution, elimination of the need for magnetic field switching; 2) better sample preparation. The sensitivity of the technique is greatest for the highest purity specimens. Also, it is desired to have more control over the radioactivity diffusion; and 3) more sophisticated analysis techniques with direct Fourier analysis of the data into intermediate state field density maps.

VII. Data Processing Instrumentation

The interface logic and circuitry to enable multi-channel pulse-height analyzers to write out into and read back from both a Teletype 35KSR console (connected to the IBM 7094 computer Time-Sharing facilities at M.I.T.) and an incremental magnetic tape unit have been almost completed.

The analyzer data can be transferred directly to the computer's disc memory at the Teletype System limited rate of 10 characters per second. Similarly, computer data will soon be able to be read back at the same rate into the analyzer for viewing on the CRT display and possible automatic plotting if desired.

The same interface also enables the analyzers to read and write IBM-compatible magnetic tapes using a Kennedy model 1400 FR tape recorder having incremental write and continuous read-back modes and "Flux-Checking" capabilities (viz., reading back each character as it is written, comparing the result with the data at the input terminals, and stopping if a discrepancy occurs). The tape is written in "card image" BCD format (with 10 channels to the record of "card") so that it is both simply FORTRAN READable during on-line program execution and also it can be easily off-line listed on an IBM 1401-1403 fast printer setup using the standard system listing program. This latter capability means that a 4096-channel dump may be listed in 10-columnar format in less than a minute, at a 600 lines/min. rate (vs. 3/4 hour on a typewriter with 8-10 lines/min. rate). Non-numeric characters are ignored upon read back, so tape writing (for read back into an analyzer) is relatively unrestricted as to format. Circuitry within the interface detects and eliminates EOR-gap longitudinal check characters. (W.R. Neal)

VIII. Accurate Measurement of Total Internal Conversion Coefficients in Some Heavy Even-Even Nuclides

An experiment to measure the total internal conversion coefficients of the 2+ to 0+ transitions from the first excited levels to the ground levels of $Rn^{220,222}$, Ra^{224}, Th^{228}, and $U^{234,236}$ has recently been completed.

Thin α-ray sources of Ra^{226}, Th^{228}, U^{232}, Pu^{238}, and Pu^{240} of 1 μCi strength were prepared on 1/4 mil aluminized mylar backing at AERE, Harwell, under the direction of Mrs. Kathleen Glover. The full widths at half maximum of the α-ray spectral peaks were typically 20 keV, using a surface barrier detector, a low-noise charge sensitive preamplifier, a double delay-line main amplifier, a post bias amplifier, and a 400-channel analyzer to detect and analyze the signals.

The spectrum of γ rays emitted following population of an excited level by an α-ray transition was recorded on a 400-channel analyzer. A block diagram of the electronics is shown in Figure 6.12. A surface barrier detector was used to detect the α rays, and a 3" x 3" NaI(T1) crystal was used to detect the γ rays. Time coincidence between the signals was established using zero-crossover fast coincidence circuitry. A resolving time of 1.0×10^{-7} sec was used for the transitions in $Rn^{220,222}$ and Ra^{224}. The resolving time for $U^{234,236}$ and Th^{228} was 1.6×10^{-7} sec. To establish that the time coincidence occurred simultaneously with the population of an excited level, a slow coincidence was required between the fast coincidence output and the α rays populating the excited level. The output of the slow coincidence circuit then closed a linear gate and let the γ-ray signal pass through to the 400-channel analyzer.

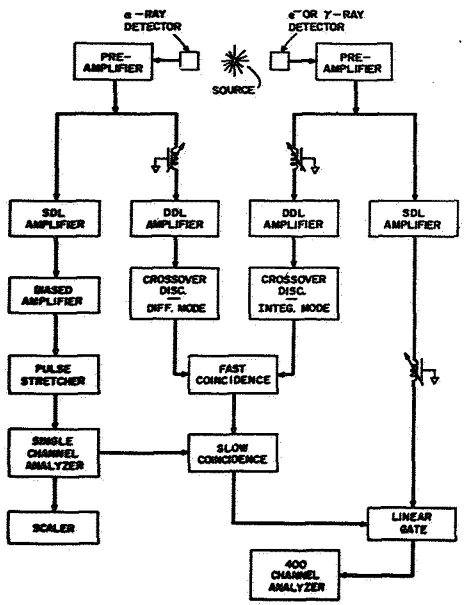

Figure 6.12

Block Diagram of Electronic Instrumentation for α-γ Coincidence Measurements

Because the α-γ angular correlations of the 0+ - 2+ - 0+ sequences studied in this experiment are anisotropic, the angular correlation was measured for each isotope. To determine the correlation, the source and α detector were placed in a cylindrical aluminum vacuum chamber (0.020" window) which could be rotated. When centered, the source lay at the intersection of the detector axes and the chamber axis. Measurements of the coincidence rate were made at 15^0 intervals, starting with 120^0 between the detector axes and ending with 240^0. Corrections were applied for the finite solid angles and for coincidence losses due to high singles counting rates in α and γ sections of the circuitry. A polynomial of the form $A_0 + A_2P_2(\cos \vartheta) + A_4P_4(\cos \vartheta)$ was fit to the ratio $N_\gamma(\vartheta)/N_\alpha(\vartheta)$ where $N_\gamma(\vartheta)$ and $N_\alpha(\vartheta)$ are respectively the detection rates of de-excitation γ's and of α's which populate the excited state.

Expressions for A_0, A_2 and A_4 can be derived from the theoretical angular correlation function for point detectors. $W(\vartheta) = 1 + a_2P_2(\cos \vartheta) + a_4P_4(\cos \vartheta)$. These expressions are functions of P_γ, a_2 and a_4 where P_γ is the probability than an excited level decay by γ-ray emission. Setting the expressions equal to A_0, A_2, A_4 gives three simultaneous equations which can be solved for P_γ, a_2, and a_4. The total conversion coefficient is then

$$\alpha_{tot} = \frac{1-P_\gamma}{P_\gamma}.$$

The data are presently being analyzed and preliminary results indicate agreement with the theoretical values of Sliv and Band. (R. Schlenker)

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Eduardo Jorge Ansaldo, "Investigation of Mössbauer Angular Distributions", S.M. in the Department of Physics, May, 1967.

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Gatti Channabasavappa Pramila, "Nuclear Moments and Hyperfine Interactions", Ph.D. in the Department of Physics, September, 1967.

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David Kwaku Yeboah-Amankwah, "The Study of Nuclear Isomer Shift in Low Lying Excited States of Deformed Nuclei Using Mössbauer Effect", Ph.D. in the Department of Physics, January, 1967.

CYCLOTRON GROUP

I. Cyclotron Operation and Equipment

A. Cyclotron Operation

During the past year cyclotron beam stability has been improved by the addition of a current-regulated power supply for the proton and deuteron ion source arc and an automatic radio-frequency balancing system for the dee voltages.

Since the ion source was shaped for maximum alpha beam efficiency it is very stable for alpha particles. However the proton or deuteron arc requires far less power and, under these conditions, was very unstable. Furthermore slight variations in arc current varied the loading of the oscillator system causing voltage changes in the dees. The addition of a current-regulated power supply for use with the proton and deuteron arc eliminated this instability.

During normal operation the movement of the dees, caused by heating, changes the radiofrequency balance of the push-pull oscillator system over a period of time. The correction for this has been manually controlled from the console by means of a motor driven elevation adjustment of one dee. To make operation of the cyclotron more stable it was decided to make this correction work automatically. In order to do this it was necessary to derive a signal from the differences of the two plate currents of the oscillator tubes. This system has been working properly for over six months and has made cyclotron operation more stable and convenient. (F. Fay, B. Bucelewicz and E.F. White)

B. Ge(Li) Detectors

Work has continued on the production of lithium-drifted germanium gamma-ray detectors. At present we have a 7cc detector which gives us 3 keV resolution on the Co^{60} lines and a ~32cc with about 5 keV resolution on Co^{60}. Two more larger (~32cc) detectors are in process. During the course of the year we have rejuvenated two 5cc detectors and the 7cc detector after vacuum failures. One interesting result has been that the gamma ray efficiency of the 32cc Ge detector is approximately six times greater than our 15cc detector. (W. Bucelewicz and W.J. Kossler)

C. Read Electronics for the Analyzer-Buffer Tape System

A system has been designed and constructed that allows us to analyse data that has been read onto magnetic tape event by event. The data so far handled by this system consist of 18 bit word records. Each 18 bit word corresponds to a pair of pulse heights: 8 bits for one pulse height and 10 bits for the other. In a typical case the 8 bit part represented the energy of a proton and the 10 bit part the energy in a gamma-ray detector for a (p,p'γ) experiment. When reading back, a window is placed around one of the inelastic proton peaks and one then obtains the coincident gamma-ray spectra associated with one excited state only. The system uses Digital Equipment Corp. Flip Chip Modules and has been designed to be quite flexible. (W.J. Kossler and B. Annese)

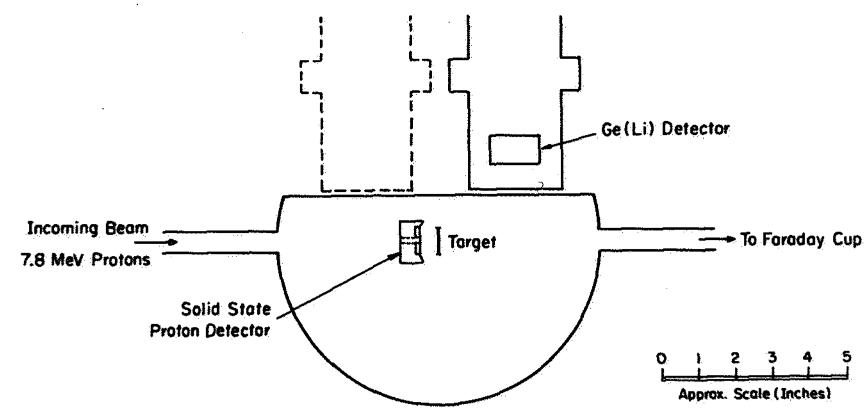
II. GAMMA-RAY STUDIES

A. Ca^{42}(p,p'γ)

This experiment was mentioned in last year's progress report. In the past year more data has been obtained, using an annular proton detector of approximately 1/2 sr solid angle and the 32cc Ge(Li) detector. The experiment arrangement is shown in Fig. 7.1. We have used the Doppler shift attenuation method to measure the mean lives of several states. Data for branching ratio and lifetimes now cover states up to approximately 4 MeV in excitation energy. The Read Electronics for the Buffer-Tape System, discussed in the Equipment section has been used extensively for the analysis of this data. Two senior theses have been written and a paper is being written. (W.J. Kossler, M. Slade, M. Weissberger, J. Winkler, and C. Kavaloski)

B. Ca^{44} and Cr^{52} (p,p'γ)

Ca^{44} has four neutrons and no protons in the $f_{7/2}$ shell, while Cr^{52} has four protons and eight neutrons. It is therefore expected that the structure of nuclei should be similar and, in fact, their spectra are. We have used the (p,p'γ) reaction to study these nuclei in the same arrangement as for Ca^{42}. We have measured by the Doppler shift attenuation technique the mean lives of several states. In particular for the 2.655 MeV state in Ca^{44} we found $\tau_m = (3.7 {}^{+2.3}_{-1.5}) \times 10^{-13}$ sec and for the 3.161 MeV state in Cr^{52} ($\tau_m = 8.3 {}^{+9.7}_{-4.7}) \times 10^{-14}$. Figure 7.2, shows our data for the 2.655 MeV state in Ca^{44}. The line through the points is a fit using a gaussian line shape. Channel number zero is very near the energy zero. A master's thesis has been written and an abstract has been submitted to the Chicago Meeting of the American Physical Society. (W.J. Kossler and M. Slade)



SCHEMATIC EXPERIMENTAL ARRANGEMENT

Figure 7.1

Schematic experimental setup for (p,p'γ) reactions.

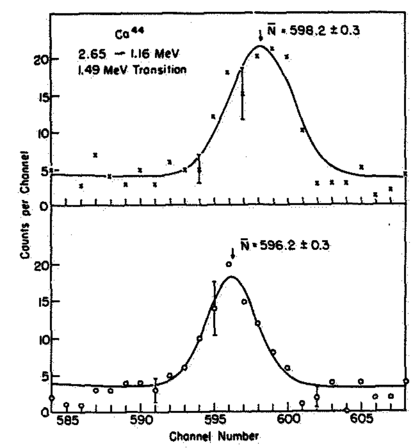


Figure 7.2

Doppler shift data for a γ-ray transition in Ca^{44}.

C. $(\alpha, \alpha' \gamma)$

Studies pertaining to this class of experiments have been carried out. Since (α, α') scattering is strongly forward peaked and because it may be necessary to use Ge detectors for the gamma-rays we have investigated the problems associated with a large solid angle (~ ½ sr) in the forward hemisphere. Gamma-ray background has been studied for the situation where 30 MeV α particles are stopped in Be, Ta, and Pb. Pb leads to the least background, and most of these gamma-rays are of low energy so it is felt that they may be effectively shielded against. We are continuing this study. The hope is to be able to observe the decay properties of those collective states which are strongly excited by α particles, e.g., 3^- states. (J. Alster and W.J. Kossler)

D. Er^{167} $(\alpha, 3n\gamma)$ and $(\alpha, 3n\gamma\gamma)$ Yb^{168}

When an alpha particle enters a nucleus and forms a compound nuclear state the relative distribution of angular momentum is easily calculated. There are fairly simple theories which predict how these distributions change as neutrons are boiled off and gamma ray cascades de-excite the nucleus. One can obtain information on the final angular momentum distribution for Yb^{168} by observing the differential feeding to various members of the ground state rotational band. In this experiment, these rotational gamma rays were observed directly ("singles experiment") and in coincidence with the cascade gamma rays ("coincidence experiment"), the point of the latter being to detect possible differences in the cascade spectra in coincidence with each rotational line. Data has been obtained and is presently being analyzed. (C.D. Kavaloski, C.F. Williamson and W.J. Kossler.)

III. (α, α') Reactions

A. Mo^{92}

An (α, α') experiment in Mo^{92} has been completed. Five new 3^- states have been identified including an unresolved doublet at 5.82 MeV. Two new 2^+ and two new 4^+ states have also been identified. These results together with those of the Zr^{90} (α, α') experiment formed a Ph.D. thesis (E.J. Martens). Fig. 7.3 shows the experimental 2^+ and 4^+ strengths in single particle units.

In previous studies in the Ca isotopes and in Zr^{90} evidence was found for the fractionization of the octupole strength. Figure 7.4 compares the experimental 3^- strengths found in Zr^{90} and Mo^{92} with each other and with theoretical estimates.[1] We note the qualitative

1. C.J. Veje, Mat. Fys. Medd. Dan. Vid. Selsk. 35, no. 1 (1966).

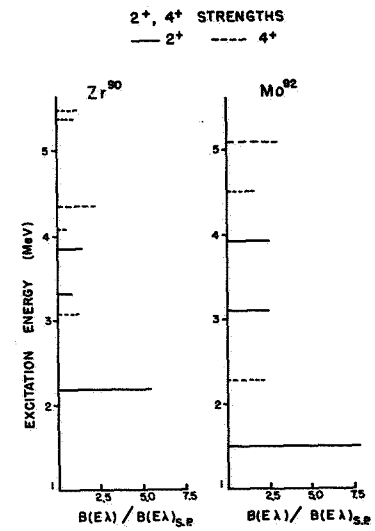


Figure 7.3

Experimental transition rates (in single particle units) for 2^+ and 4^+ states in Zr^{90} and Mo^{92}.

agreement between theory and experiment. In compairing the Mo^{92} results with those previously obtained for Zr^{90} we note even greater fractionization. This is what was anticipated because the two extra protons in Mo^{92} can also couple to 3^- states.

A paper on the (α, α') reaction in Zr^{90} and Mo^{92} is now in preparation.

B. $Ge^{70,72}$

A Ge^{70} foil was purchased from the Oak Ridge National Laboratory. This foil broke almost immediately due to local heating when exposed to an average alpha beam (0.25 μamp). We therefore undertook the development of Ge targets able to withstand the full alpha beam. We found that annealing the foils would make them less susceptible to mechanical and thermal stresses. Ge foils annealed in vacuum at 480°C withstood alpha beams of 0.3 μ amps. Successful (α, α') experiments on Ge^{70} and Ge^{72} were carried out and the results are being analyzed.

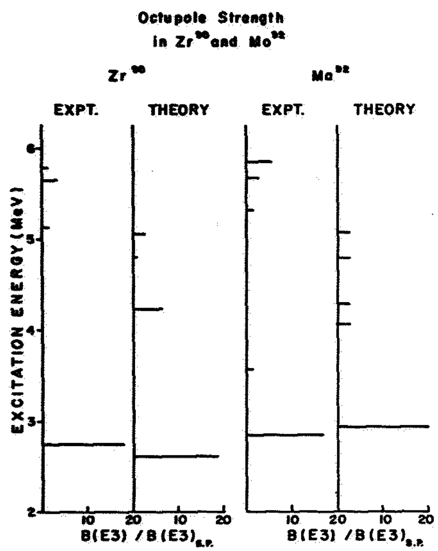


Figure 7.4

Experimental and theoretical transition rates (in single particle units) for 3^- states in Zr^{90} and Mo^{92}.

C. Sn^{118}

An (α, α') on Sn^{118} has been performed. This experiment was carried out to study the fractionization of ocutpole state in nuclei above Zr^{90}. States at excitation of 0.00, 1.209, 2.359, 2.525, 2.63, 2.79, 3.03, 3.13 and 3.68 MeV in Sn^{118} have been observed. The analysis of the data has not been completed.

D. Ti^{48}

One of the most interesting results found this year is in Ti^{48}. There 7 octupole levels have been found with the strongest being only ≈ 3 single particle units in strength. Thus it appears that in the middle of the $1f_{7/2}$ shell the "octupole mode" of excitation does not exist. One possible interpretation of this is that there isn't a closed shell core in Ti^{48}. The hypothesis has been made that this indicates Ti^{48} results can only be made when the fractionization of the octupole states in the Ca isotopes is given and when the rapid decrease in the

strength in going from Ca^{40} to Ca^{48} is understood. A paper on the Ti^{48} (α, α') reaction is in preparation.

E. The Relative Sizes of Ca^{40} and Ca^{48}

The relative sizes of Ca^{40} and Ca^{48} have been measured by the elastic scattering of 28 and 31 MeV α particles. As can readily be seen from the data (Fig. 7.5) we find that Ca^{48} is significantly larger than Ca^{40} because the diffraction pattern of Ca^{48} is shifted to smaller angles than that of Ca^{40}. This contrasts with electron scattering and μ-mesic x-ray results, which shows that root mean square radius of Ca^{48} is smaller than that of Ca^{40}. Since α-particles interact equally with neutrons and protons while electrons and μ-mesons interact with the protons only the combined results can be taken to indicate that the neutrons in Ca^{48} have a larger spatial extent than the protons.

For the data shown in Fig. 7.5 we have obtained optical model fits (as shown) using a Woods-Saxon potential. For both Ca^{40} and Ca^{48} V=45 MeV and W-10 MeV. For Ca^{40}, R=5.81 fm and a=0.58 fm. For Ca^{48}, R=5.94 fm and a=0.59 fm. So Δa is consistent with zero and $\Delta R \cong 0.15$ fm. (E.J. Martens, C. Moazed, C. Thorne, B. Cox and A.M. Bernstein)

III. (p, d) and (p, t) Reactions at 26.5 and 40 MeV

(p, d) and (p, t) reactions have been studied to obtain nuclear structure information and to study the systematics of the two nucleon transfer reaction.

To perform these experiments we had to use other cyclotrons to obtain higher energy proton beams. The experiments at 26.5 MeV were performed at the University of Colorado in collaboration with M.E. Rickey. The experiments at 40 MeV were performed at the Oak Ridge National Laboratory in collaboration with P.G. Roos. Most of our data was taken with counters and had 100 keV resolution. During the past summer a 40 MeV magnetic spectrometer run was made on Pb^{208} and Ca^{42} with 40 keV resolution. Nuclei were chosen for this study which were likely candidates for shell model calculations and generally were of closed shell, near closed shell, or single closed shell character. Since we have a lot of data we shall commit briefly only a few completed results.

To interpret out (p, t) data we have written a computer program which calculates the form factors for the two nucleon transfer reaction. This program can handle wave functions of a Woods-Saxon potential so that the asymptotic region of the form factor has the proper behavior. This enables us to compute two nucleon transfer reactions in cases where model

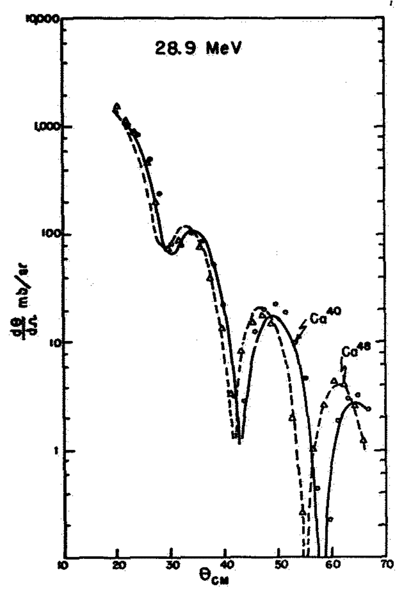


Figure 7.5

Elastic scattering of 28.9 MeV α particles from Ca^{40} and Ca^{48}.

The curves are optical model fits to the data using a Woods-Saxon potential as described in the text.

wave functions of the initial and final states are available. An example of the use of this program will be given in the discussion of the $Pb^{208}(p,t)Pb^{206}$ reaction below and in the $K^{39}(He^{3},p)Ca^{41}$ reaction discussed by the ONR Generator group.

A. The $Ca^{42,44}$ (p,d) Reaction at 26.5 MeV

The analysis of this experiment has been completed. An interesting result of this experiment is the location of a second $f_{7/2}$ state near 3 MeV in $Ca^{41,43}$ with approximately 1/10 the strength of the ground state transition. These pieces of the $1f_{7/2}$ single particle strength were not seen in the $Ca^{40,42}$(d,p) reactions. The result for Ca^{41} was predicted by the calculations of Gerace and Green who include combinations of spherical and deformed wave functions in their theory.

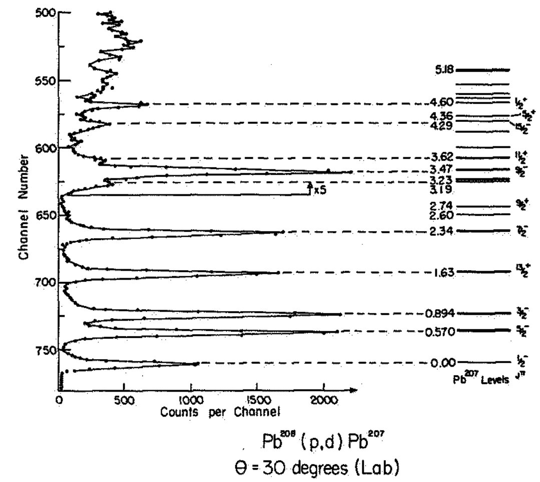


Figure 7.6

Deuteron spectrum from the $Pb^{208}(p,d)Pb^{207}$ reactions at 30^{o} lab.

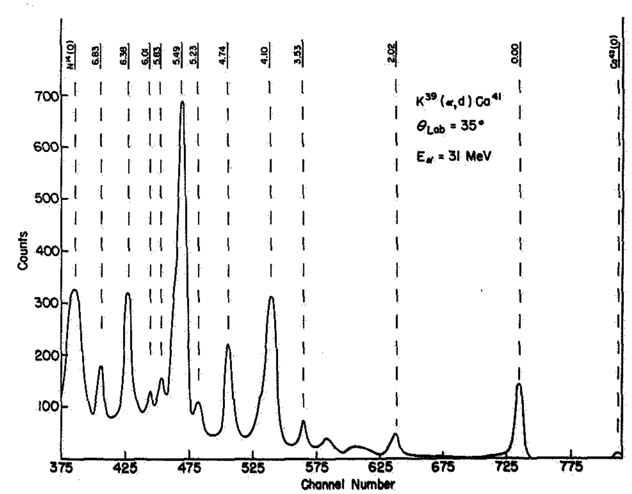


Figure 7.7

Deuteron spectrum from the K^{39} (α, d) reaction at 35^{o} lab.

This experiment also has located the $2s_{1/2}$ and $1d_{3/2}$ hole states in $Ca^{41,43}$. These states lie at relatively low excitation energies and have not been explained theoretically. The data on these non-normal parity states represents a challenge to nuclear model calculations.

A paper on this subject will be ready for publication in the near future.

B. The $Pb^{208}(p,t)Pb^{206}$ Reaction at 40 MeV

This reaction was studied to test the validity of Pb^{206} wave functions which are assumed to be two neutron holes in the Pb^{208} closed shell. A solid-state counter experiment with 100 keV resolution was performed. The experimental results have been compared with the predictions of three sets of theoretical wave functions. All three sets of predictions give reasonable agreement with experiment. The wave functions employed were not vastly different from each other and in particular the signs of the main components of the wave functions were all the same. The primary conclusion is that we have a reasonable description of Pb^{206} and that the (p,t) reaction is primarily sensitive to the signs of the wave function amplitudes.

C. The $Pb^{208}(p,d)$ Reaction at 40 MeV

This reaction was studied with 100 keV resolution. A spectrum at 30 degrees is shown in Fig. 7.6. The six one-hole states that were anticipated were strongly excited. In addition five more states were seen with approximately 5% of the intensity of the strong states. These states represent deviations from the simple shell model picture of Pb^{208} or Pb^{207} or both.

(S.M. Smith, C. Moazed and A.M. Berstein)

IV. The $K^{39}(\alpha,d)$ and (α,t) Reactions

The vacuum evaporation of potassium on carbon foil, which was developed by L. Khun as part of his senior thesis, was carried out above the scattering chamber. This arrangement permitted one to transfer the target to the scattering chamber under continuous vacuum. The (α,d) and (α,t) reactions on K^{39} were studied with 31 MeV incident α-particle beam and with an average resolution of 150 keV. A ΔE-E telescope consisting of 250 and 2300 micron silicon surface barrier detectors was employed in the identification of deuteron and triton spectra. Angular distributions of deuteron and triton spectra were obtained in intervals of 5° from 15° to 50°. In the $K^{39}(\alpha,t)Ca^{40}$ reaction levels at 0.00, 3.73, 4.48 and 5.62 are strongly excited. A preliminary analysis of (α,d) reaction indicates that levels or groups of levels at 0.00, 2.02, 3.53, 4.10, 4.74, 5.49, 6.38 and 6.83 MeV are strongly populated or isolated. The deuteron spectrum at 35° is shown in Fig. 7.7. Due to the selection rules for the (α,d) reaction these

levels correspond to $\Delta T=0$, $\Delta S=1$ transfers. Levels which are seen in the $K^{39}(He^3,p)$ reaction and not in the $K^{39}(\alpha,d)$ reaction, such as the 3.74 and 4.83 MeV levels, imply $\Delta T=1$, $\Delta S=0$ transfers. Further comparisons between the (α,d) and (He^3,p) and one nucleon transfer reactions leading to Ca^{41} and the analysis of the angular distributions are in progress.

(C. Moazed and A.M. Bernstein)

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THEORETICAL GROUP

Introduction

The theory group has maintained its interest in the important contemporary problems in particle and nuclear physics. Significant contributions in both areas have been made. These are detailed in the summary presented below or may be gleaned from the abstracts which follow.

As in the past we have had a substantial number of post-doctoral fellows. In addition there were a substantial number of senior visitors. These included Donald Geffen of the University of Minnesota, L. S. Kisslinger of the Case-Western Reserve University, I. Muzinich, now at Rockefeller University, W. True of the University of California at Davis and J. Weneser of Brookhaven National Laboratory. This very substantial group of superb theorists greatly amplified our effectiveness and scope. It is a pleasure to record the prevalence of a lively and stimulating atmosphere which contributed greatly to a most productive year. The active interaction between the specialists in nuclear theory and particle theory has always been a major source of strength of the theoretical group. This interaction has further been encouraged by the initiation in this year of a joint journal club in which recent papers and preprints in both fields are reviewed.

The theoretical group has received important assistance from the Physics Department, from Provost Wiesner and President Johnson. At the suggestion of Prof. Weisskopf, the head of the Physics Department, the Provost and President have authorized a transformation of the quarters housing the theoretical group as well as some of the other theorists in the department. A new environment has been established which provides a "home" for the group and which maximizes the opportunities for communication and collaboration. New quarters were also provided for the graduate students and research assistants in theory. This change has contributed measurably toward the creation of a "good" atmosphere and is deeply appreciated by all the members of the group.

We turn now to a summary of the research completed in the last year. We begin with nuclear theory.

Nuclear Forces (abstracts I-V): The fundamental goal of nuclear theory is the explanation of nuclear phenomena in terms of the forces acting between the nucleons making up nuclear systems. A description of nucleon-nucleon forces is a prerequisite for this study. In the past year the consequence of this force for the electromagnetic properties of the deuteron and of the neutrons are examined. Of particular importance is the result that the neutron electric form factor obtained from elastic electron deuteron scattering now extrapolates smoothly with decreasing momentum transfer to the thermal value removing an outstanding difficulty. Present analysis gives only a rough description of the nuclear forces when the nucleons are close

together. Studies of a non-local description for this interaction are now underway as well as the development of improved theoretical forms for the larger separation distances and the effect of inelasticity at the higher energies.

Nuclear Structure and Nuclear Forces (abstracts VI-XI): Starting from various alternative forms calculations have been made of the consequent nuclear structure. Hartree-Fock calculations for several 4n nuclei have been made using the non-realistic Tabakin potential. When a second order correction to the Hartree-Fock results coming principally from the tensor forces is included excellent agreement with the binding energy of these nuclei is obtained. A soft-core realistic potential does not give satisfactory results. Hard core potentials must be attacked by more sophisticated methods. Two approaches have been studied here. One is based on the Eden-Emergy modification for finite nuclei of the Brueckner method. Another obtains an effective force which can be used in the Hartree-Fock calculations by a modification of the Scott-Moskowski treatment for the singular short range components, to which is added the well behaved long range part as well as a second order correction for the tensor force. The results obtained with both of these methods are most encouraging. On the other hand it must be noted that both also involve a number of assumptions of uncertain validity. In particular, it is not clear that these methods achieve self-consistency or are consequences of variational principle.

Similar methods are now being used to calculate excited states of nuclei. Of particular interest are the isotopes of Ca for which considerable experimental evidence is available and for which the theory can be simplified.

Models and the Hartree-Fock Approximation (Abstracts XII-XXIV): In the preceding section we have discussed the calculations which attempt to relate nuclear properties with the Hartree-Fock approximation. A second step would be to improve upon the approximation and what is much the same thing to relate various phenomenological models with the Hartree-Fock results. Of course, further elaboration of models goes on simultaneously. We mention here a number of items involving these various elements.

The Bohr-Mottelson theory of rotational states is such a phenomenological model. In attempting to base it on the Hartree-Fock approximation one must solve the problem of separating the intrinsic and rotational variables. This problem has been resolved, with the development of an expression for the moment of inertia which is in substantial agreement with the results of time-dependent Hartree-Fock theory.

Within recent years an improvement on the Hartree-Fock approximation known as the random phase approximation (R.P.A.) has been developed. The R.P.A. is essentially a small vibration analysis about the stationary Hartree-Fock solution. The R.P.A. introduces 2p-2h correlations into the ground state wave function. These correlations are found to introduce important corrections to electromagnetic transition rates. It reduces the transition rate of the giant dipole strength in O^{16} and leads to an appreciable transition strength above the giant resonance region.

Both the shell model and collective model have been tested and extended. In the shell model the nucleus Pb^{206} is described in terms of two neutron hole orbitals moving in a central potential and interacting via a residual force. It was found that a residual force consisting of a singlet even central force, a triplet-odd central force plus a P_2 force gave good agreement with the low-lying levels of Pb^{206}. Quasi-particle techniques were used to describe odd-odd nuclei in the A=120 region. The odd quasi-proton and quasi-neutron were allowed to interact. It appears that the level structure is very sensitive to the details of this interaction. Finally the core-excitation for Bi^{209} model was studied where weak coupling between the 3^- phonon state in the Pb^{208} and the $h_{9/2}$ proton was assumed. The experimentally observed level order was not obtained.

In the collective model the transition region between vibrational (Pt) and rotational nuclei (W) was investigated. This work was done in collaboration with M. Baranger of Carnegie-Mellon University. The parameters of the Bohr-Hamiltonian were calculated using pairing plus quadrupole interactions and the corresponding equation was integrated numerically. A number of phenomena were discovered. These showed large deviations from the naive description of the rotational and vibrational nuclei. Substantial agreement with recent experimental work was obtained.

Scattering and Reactions (Abstracts XXVI-XXXVIII): We can break up the considerable effort of the group in this area into three aspects. Improvements have been made with regard to description of nuclear reaction mechanisms. Investigations exploiting these for some particular reactions have been performed. Finally attempts have been made to determine the residual interactions which are involved in nuclear collisions.

The doorway state description of nuclear reactions has been improved by including the direct coupling between the open channel and the fine structure states as well as the indirect coupling which proceeds via the doorway state. After averaging over the fine structure states, the interactions in coupled equations describing the interaction among the open and doorway channels become complex.

Coupled equations have been used to describe isobar analog resonances. The effects of coupling to other collective states have been included so far as energy dependent interactions modifying the original coupled isobar analog resonances.

Particle exchange reactions such as deuteron stripping, and indeed any reaction involving composite systems have posed extremely general and important problems. In one research effort particular attention is being paid to the effects of the Pauli exclusion principle. In another a linked cluster expansion of the scattering matrix including both deuteron stripping and scattering by a complex system has been obtained. These are perturbation series. In the case of deuteron scattering the first term of the generalized optical potential is the convolution of the sum of the neutron and proton optical potentials and the deuteron wave function.

Turning back to nucleon-nucleus scattering a significant result has been the development of a theory which does not expand the solution in terms of the states of the target nucleus. It has the virtue of putting the calculation of the bound and scattering states of a system on the same footing.

The exploitation of high energy probes for nuclear structure studies is of great interest in part because of the expected advent of the 400 MeV electron linac at MIT. A recent study here includes an investigation of the quasi-elastic (e, e'p) experiments to see if these show effects of nuclear correlations. Improvements in high energy optical model calculations and their generalization so as to include inelastic events such as the excitation of vibrational levels have been obtained. Developments in multiple scattering theory so as to make practical the inclusion of off the energy shell processes is in progress. It is expected that the effect of these terms will be sensitive to the nature of the nuclear correlations.

Parity Nonconservation in Strong Interactions (abstract XXXIX): Here we study the possibility that the strong nuclear forces have a weak non-parity conserving component. This possibility is indicated by the present theories of weak interactions. An experiment in which this effort may be observable is the radiative capture of neutrons by deuterons.

(b) Elementary Particle Theory

Elementary particle physics is now searching for the appropriate variables for the description of the spectrum and interactions of the meson and baryon resonances. Several schemes have been conjectured each with its initial area of success. Much of the research reported below involves further development of each of these theories, and most important, to the intercomparison between them. Concurrent with this fundamental research, extensive analysis of experimental data employing various models have been made with some important successes. We also include in this section research which is concerned with the possibility of a finite quantum electrodynamics.

Quark Model (abstract XL-XLIV): The quark model provides a realization of the many of the more abstract models of elementary particles. For example, important features of current algebra as well as group properties may be very naturally incorporated in such a model. It permits explicit calculations although it should be noted that these will involve additional assumptions usually based on fairly definite semi-empirical theoretical descriptions. On the other hand these calculations provide definite relations between the decay probabilities for mesons and for baryons. The success which has been obtained in correlating these decay probabilities for weak, electromagnetic, as well as strong interactions is indicative of the validity of the model. On the negative side of the ledger is the result that the quark model with fractionally charged quarks as used above does not yield finite radiative corrections to the beta decay of neutrons, while a model with integrally charged quarks does.

The Angular Momentum Plane (abstracts XLV-LX): The original hypothesis that the motion of Regge poles in the S matrix with energy would suffice to explain the energy dependence of cross sections was based on an analogy with S matrix properties for non-relativistic potential scattering. It is now clear that the structure in the elementary particle case as well as for the non-relativistic many body problem is much more complicated. Exchange of Regge poles leads to Regge cuts. When the particles interacting have unequal masses, daughter Regge trajectories are required. The independence of the amplitudes associated with differing Regge trajectories is not consistent with crossing. Consistency relations are implied; their satisfaction is described by the terms "conspiracy" and "evasion".

Pure Regge behavior of scattering amplitudes excludes fixed poles at right signature nonsense points in the angular momentum variable, J. (Recall that a nonsense value of J is a value below the physical minimum, e.g., J=-1, or, in a problem with spin, $^3(J)_J$ at J=0, etc. Right signature means appropriate even or odd J, such as even J in π_0-π_0 scattering, odd J in I=1 π-π scattering, etc.) The mechanism excluding such singularities is unitarity, which requires F(J) to be finite for all real J and energy above threshold. In weak processes, calculated to finite order in a small coupling constant, the unitarity bound is absent, and fixed poles may occur.

The theorists here have been very actively concerned with these questions. The discovery of polarization in π-nucleon charge exchange scattering as well as the sharp break in the logarithmic derivative of 90 degree proton-proton scattering cross section can be explained in terms of Regge cuts generated by known particles and the "Pomeranchukon". Effects of "conspiracy" in the comparison of the data obtained for $pn \rightarrow pn$ and $p\bar{p} \rightarrow n\bar{n}$ reactions seem to require conspiracies *of branch cuts in the angular momentum plane rather than just pole conspiracies. Analysis of* high energy photoproduction seems to require a pole as well as cut conspiracy. The existence of fixed poles for weak and electromagnetic interactions was discovered here. Models have been constructed which show this phenomenon. In the case of the electromagnetic interaction a fixed pole was shown to be required in order for the total photon cross section to approach a finite (rather than zero) limit for high energy photons.

Regge theory is employed to establish the "superconvergence" of certain dispersion theory integrals. The effect of the existence of branch cuts in the angular momentum planes on these convergence considerations is of obvious importance.

(c) Current Algebra, P.C.A.C., Soft Pion Phenomena (abstract LXXII-LXXIX)

Current algebra assumes that the basic dynamical variables to be used in the description of elementary particle phenomena are the hadronic currents observed in weak decays. These currents are assumed to obey commutation rules. In these terms, the fundamental problem of particle physics in the determination of these currents and commutation rules. The assumption of conservation of vector currents and of the "partial" conservation of axial currents, dispersion theory, particularly superconvergent relations derived with the aid of the asymptotic behavior

given by the Regge hypothesis, provides the necessary tools. Typical results which are obtained include sum rules which in turn yield relations between coupling constants and form factors. When the pions are assumed to have zero mass, one obtains a description of soft pion emission similar to that used for the description of photon emission, i.e., for bremsstrahlung. The zero pion mass limit is particularly of value in calculations which may be so formulated as to be relatively independent of the pion mass.

The calculation of the electromagnetic mass difference was carried out in the off limit zero pion mass with excellent results. This has stimulated a number of calculations attempting to take the finite mass of the intermediate pion into account as well as to evaluate corrections of higher order in the charge.

Current algebra techniques have been used to derive sum rules for spin-flip pion-nucleon scattering amplitudes and for the two $A\rho\pi$ coupling constants. The vertex functions for axial and axial vector currents in both the soft and non-soft pion limits are under investigation.

Some Phenomenological Approaches (abstracts LXX-LXXIII): We have already mentioned a number of successful fits of data employing Regge poles and branch cuts. In addition quantitative fits for the photonucleon production of π^0, $\pi^{\pm}$, K^+ have been obtained using an absorption model which combines diffraction theory and a one particle exchange mechanism. The incoherent droplet model has been used to calculate multiparticle production. The boundary condition model prediction of a peak in the K^+N interaction has been recently verified at Brookhaven.

Quantum Electrodynamics, Field Theory (abstracts LXXIV-LXXX) : Earlier work on the possibility of finite quantum electrodynamics is being continued. Of possible importance for these calculations is the conformal symmetry of the field equations in the limit of zero electron mass. This symmetry is being exploited in the calculation of the divergent part of the vacuum polarization.

Electron-positron scattering in the back direction is sensitive to proper treatment of higher order effects in quantum electrodynamics. This scattering has now been calculated to fourth order.

Three-Body Problem (abstracts LXXXI-LXXXIII): The effect of three body states on pion-nucleon scattering in a model which satisfies unitarity has been investigated. Another model has been used to study the continuation into the complex angular momentum plane of the amplitude for the scattering of a particle by a two particle bound state.

I. Nucleon-Nucleon Cores

We have found a variety of ways in which the core region of the nucleon-nucleon force can be handled using separable non-local forces. It appears to be possible to fit the two nucleon data so that the nuclear shell model problem can be undertaken with ordinary perturbation theory. However, this is for the $^1S_0$ state only and work is continuing on the others. It should be remarked that the potential obtained gives a very good fit to the $^1S_0$ phase shift. (B. Levy, A. K. Kerman and B. Rouben)

II. Improving the Theoretical Nucleon-Nucleon Potential

Charap and Fubini have noted that the two meson exchange Feynman diagrams do not permit a convergent expansion in μ/M. However, we can show that there is an asymptotic series for these diagrams in which the nonexpandable terms are of the order of $e^{-\mu/M}$. Those terms are small for pion exchange justifying the use of the expansion for the accuracy previously required. The accuracy achieved is probably insufficient for further use largely because of the strong cancellation between the leading order two-(nucleon) pair term (μ^2/M^2) and the leading order one-pair term (μ^2/M^2). The higher order terms then become important and are not yet evaluated. Instead of continuing the expansion it is more accurate, and probably no more difficult to evaluate the potential without any expansion in (μ/M) using the dispersion equation with a perturbation spectral function. This has the further advantage of permitting the representation of rescattering corrections by π-N amplitudes. However, the already evaluated results are not sufficient to our purpose. The potential so obtained is much too strong to fit experiment as no mechanism for pair suppression is present. Using projection operators we are separating the time ordered parts of the perturbation spectral function. The two-pair part has been evaluated and is similar to the contribution of the leading order in μ/M of the old potential. Momentum dependent contributions are also being evaluated. (E. Lomon and H. Partovi)

III. Coupled Channels in the Nucleon-Nucleon Interaction

Coupling to meson production channels is expected to affect the elastic scattering well below the region of strong inelasticity and even below threshold. In the approximation that many particle channels are treated as two particle channels of variable mass, the formalism for solving the multichannel Schroedinger equation has been developed for the realistic potentials and internal boundary conditions, including the Coulomb interaction. Computer programs are being written that can easily handle the two to five coupled channels that may be important at less than 2 BeV energy. An analysis will be made of elastic and inelastic data below a BeV laboratory nucleon energy. (E. L. Lomon)

IV. Electromagnetic Predictions of a Nucleon-Nucleon Interaction

It has been shown[1] that two nucleon data, below 400 MeV laboratory energy, are well fitted by a one boson plus two pion theoretical potential exterior to an energy independent boundary condition. Examination of predictions for two nucleon electromagnetic effects tests the validity of that interaction off the energy shell. The model obtains as low as 4.5% D state for good fits to scattering, deuteron binding energy and quadrupole moment. Thus the deuteron magnetic moment is understood without recourse to meson current effects larger than theory indicates. The deuteron photodisintegration differential cross section and polarization is well fitted, and the need for a 7% D state in this context disproven. The thermal capture cross section has the usual, model independent, discrepancy which may be attributed to a meson current contribution.

The neutron electric form factor, as analyzed from low momentum transfer electron deuteron elastic scattering, is larger for deuteron wave functions with a smaller % D state. This, added to the relativistic correction computed by Gross and Caspar, extrapolates smoothly to the thermal neutron-electron value, removing a previous dilemma. At larger q^2 the data analysis is complicated by relativistic and meson current effects and the relevance of magnetic as well as electric nucleon form factors. A program to predict electron-deuteron breakup, including final state interaction, is being prepared.

Except for the Coulomb force and the difference of average pion masses in the pp, T=1 np and T=0 np systems, the model is charge independent. The exceptions are sufficient to account for the difference between the np and pp singlet scattering lengths and effective ranges, as well as the nn and pp scattering lengths difference. (E. Lomon and H. Feshbach)

V. Construction of Potentials from Given Dynamical Discontinuities of Partial Wave Amplitudes

A method is derived, which allows the determination of a potential from given dynamical singularities of partial wave amplitudes. The special examples of the one pole approximation of the left hand cut and the single nucleon-nucleon amplitudes are treated. (H. G. Dosch)

VI. H_3-He_3 Mass Difference

The perturbation theory for the Amado equation was investigated. The Amado equation is an equation for particle-bound state scattering which follows from the 3-body Fadeev equations,

1. E. Lomon and H. Feshbach, Rev. Mod. Phys. 39, 611 (1967), and Advances in High Energy Physics, Wiley, to be published.

when the two-body potential has a certain form. As an application, he considered the H_3-He_3 mass difference and showed that the effects deriving from the p-n mass difference not included in the usual calculation is small. (V. L. Teplitz and R. Yaes)

VII. Hartree-Fock Calculations of Finite Nuclei

Truncation effects in Hartree-Fock calculations have been studied by utilizing two basis sets -- one containing the 1s to the 2p-1f shell and one including also the 3s, 2d, 3p, 2f, 1g, 1h, and 1i shells. The energy, r.m.s. radius, and kinetic energy per particle is found to be quite stable, but the deformation is sensitive to the size of the space. (This work is being submitted to Nuclear Physics for publication.) New computer codes are being developed that greatly reduce the amount of time necessary for the calculation of matrix elements so that more calculations can be done -- using different forces and even larger spaces. Presently the Tabakin force, a non-local nucleon-nucleon potential fit to scattering data, is being utilized. (W. Bassichis, A. K. Kerman, with B. Pohl (LRL, Livermore, California))

VIII. Isospin Mixing in Hartree-Fock Calculations

Hartree-Fock calculations presently being performed, either limited or full angular and radial, limit the single particle functions to either proton or neutron. Whether a gain in energy can be obtained by allowing a mixture and later projecting goo T_z and T is being investigated by a numerical calculation and by solving the infinite range model. Preliminary results indicate that for reasonable forces there is no advantage to mixing for the type of nuclei considered. (W. Bassichis and A. MacKellar)

IX. Unitary-Model-Operator Approach to Nuclear Structure Physics

Hartree-Fock calculations have been carried out with an effective interaction derived from the Yale potential. The spherical nuclei O^{16} and Ca^{40} have been considered. The orbitals are expanded in terms of harmonic-oscillator functions, and the dependence of the results on the number of oscillator functions used and upon the oscillator size parameter is studied. The importance of various second-order terms is considered using a simple approximation for the Pauli operator on the energy denominators.

The details of these calculations and extensive tables of the effective interaction used are given in two papers which have been published in the Physical Review. (C. Shakin)

X. Theory of Finite Nuclei

Coupled Bethe-Goldstone equations have been solved in a single oscillator basis. Care has been taken to make as many of the intermediate states satisfy Hartree-Fock self-consistency as possible through the introduction of state dependent constants in the oscillator single particle well and treating R not as a quantity specifying the nuclear radius, but as a parameter to be varied so as to minimize the 1 particle - 1 hole states that would be zero in true Hartree-Fock. A letter was published giving, starting from the Hamada Johnston nucleon interaction, all the radial and two-body reaction matrix elements necessary for shell model calculations in the p-shell. Physically reasonable values for absolute binding energies, the shell model spin-orbit potential and the effective interaction between nucleons in light nuclei have been obtained. An extension of the Eden-Emergy approach to Bruechner theory has been made. Results for O^{16} have been obtained in which the Yale, Hamada-Johnston and Reid potentials are compared. The proton-proton correlation function is obtained, as well as the second order correction to the Eden-Emergy treatment of the exclusion principle, a correction which turns out to be small. (A. MacKellar, with R. L. Becker and B. M. Morris)

XI. Excited States of the A = 42, 43, 44 Systems

The excited states of the nuclei slightly heavier than Ca^{40} are being studied via Hartree-Fock and projection. Spectroscopic information can be obtained in this region, just as was done for the O^{16} region, by treating the doubly magic nucleus as a core, utilizing an effective force tailored for this specific region, and carrying out Hartree-Fock calculations with a small number of particles outside the core and a few holes inside the core. This has so far been carried out for Ca^{43} where low-lying states had been a puzzle. The character of these states has been determined (5p-2h) and neighboring nuclei are now being studied. (W. Bassichis, S. N. Tewari)

XII. Theory of Nuclear Rotational States

This is an attempt to derive the semi-phenomenological Hamiltonian of the Bohr-Mottelson theory of rotation from first principles. To this end, collective variables describing rotation are introduced (angular momentum-and angle-operators), and the Hamiltonian is decomposed into intrinsic and collective parts by a systematic procedure:

$$H=H^{(0)}+\Sigma_{A=1}^{3} H_A^{(1)} J_A+\frac{1}{2}\sum_{AB} H_{AB}^{(2)} J_A J_B+\ldots ; \qquad (1)$$

the $H^{(1)}$ being intrinsic operators (commuting with all collective variables). H can be diagonalized by trial functions

$$\psi_{nJM}=\sum_K \mathcal{D}_{MK}^{J*}(\theta)\,\phi_{nK}(\eta) \qquad (2)$$

$\phi_{aK}(\eta)$ being functions of the intrinsic variables η. A key element of the present approach is to express both the $H^{(i)}$ and the $\phi(\eta)$ in terms of the (redundant) set of particle coordinates. This makes it possible to express $\phi(\eta)$ in terms of Slater determinants and to make use of the Hartree-Fock approximation when determining intrinsic structure.

We end up with a scheme closely resembling the Bohr Mottelson scheme. Approximate expressions of the rotational moment of inertia are similar to the Thouless-Valatin result obtained from time dependent Hartree-Fock theory. (This work in in the process of being written up.) (G. Cooper and F. Villars)

XIII. Variational Principle for Projected Slater-Determinants

Approximate wave functions representing the states of a nuclear rotational band may be obtained by projecting a Hartree-Fock wave function (in an anisotropic potential) on fixed values J of the angular momentum:

$$\phi_J = P_J\phi \qquad (1)$$

This suggests that the determinants ϕ might better be defined as solutions of the variational principle.

$$\delta(\phi H\ P_J\phi)/(\phi P_J\phi)=0 \qquad (2)$$

rather than through the usual

$$\delta(\phi H\phi)=0 \qquad (3)$$

The program based on (2) can be implemented simply only if it is assumed that the solutions are close to those of (3). The small difference between the two trial functions however has a significant effect on the rotational level spacing: Eq. (3) combined with (1) leads to the Peierls-Yoccoz moment of inertia; by contrast we find that (2) gives the same result as the time dependent Hartree-Fock theory, namely the Thouless-Valatin moment. (N. Rogerson and F. Villars)

XIV. A Theoretical Scheme

A theoretical scheme appropriate for generalizing the Hartree-Fock and RPA theories to include ground state correlations has been developed. In this scheme an appropriate version of the Beliaev-Zelevinsky expansion is used for expanding the Hamiltonian in boson operators. The ground state wave function is defined as the independent boson wave function, which minimizes the expectation value of the hamiltonian. It follows that the ground state cannot mix with one- or two-boson wave functions, and this condition yields immediately equations generalizing the Hartree-Fock and the RPA equations. By considering the oscillations of "deformed" independent boson wave functions around the equilibrium position, the boson-boson correlations, due to

anharmonic effects, are introduced. Finally, it may be shown that the present approach possesses formal properties similar to those of the RPA theory. (J. da Providencia)

XV. Isospin Invariance and the Pairing-Force Problem

The isoscalar pairing-force Hamiltonian is studied first in the BCS-like approximation, including neutron-neutron, proton-proton and neutron-proton interactions. Constraining $<\hat{N}>$ and $<\hat{T}^2>$ we find they differ in the expectation value of $\hat{T}_z$, $-T \leqslant <\hat{T}_z> \leqslant T$. For the limit $<T_z> = T$, the minimum occurs at zero neutron-proton interaction. The residual interactions, those neglected by the BCS approximation, are treated by the quasi-boson approximation. The spurious effects of number and isospin dispersion are identified. A procedure for explicity displaying the number and isospin dependence of the energy is given, together with one for obtaining excited states with all possible isospins. Finally, as an example, the degenerate case is worked out, and agreement with the exact solution, including ground-state neutron-proton correlations, to the order considered, is demonstrated. (J. N. Ginocchio and J. Weneser)

XVI. Corrections to Electromagnetic Transition Rates due to Ground State Correlations

With the assumption that the two-particle, two-hole correlation structure of the nuclear ground state is given by the RPA result some corrections to transition rates are calculated. These corrections decrease significantly the theoretical values for the transition strength of the dipole states in O^{16} and are therefore in the direction of improving the agreement between theory and experiment. It is also found that appreciable transition strength may be obtained above the giant resonance region. Two mechanisms are considered in the later case:

a) the direct excitation of high-energy, two-particle, two-hole states proceeding via the ground-state correlations of the RPA theory, and

b) the shifting of transition strength to higher energies via the mixing of dipole states into two-phonon states at higher energies.

In addition, corrections to the calculation of the form factors for two $J=2^-(T=1)$ states of O^{16} are considered. The corrections arising from an analysis of the ground-state correlations are found to improve the agreement between theory and experiment when comparison is made to standard RPA calculations.

A paper describing this work has been submitted for publication in Nuclear Physics. (C. Shakin)

XVII. Shell Model Theory of Pb^{206}

The lower lying levels of Pb^{206} were studied in the framework of the shell model. All the neutron hole orbitals between N=82 and N=126 were considered. The two neutrons were considered to move in a central potential and to interact with each other through a residual central force. The residual central forces considered were: a) A singlet-even central force, b) A singlet-even central force plus a P_2 force which is known to arise when the particles are weakly coupled to the L=2 phonon oscillations of the core, and c) A singlet-even central force plus a triplet-odd central force plus the P_2 force mentioned above. Good agreement with experiment was found for the energy eigenvalue positions and for the ground state wave function. (W. W. True).

XVIII. Shell Model Theory of Pb^{208}

A RPA, random-phase approximation, code was written and applied to the one-hole one-particle excitations of the Pb^{208} core. Gillet, Green, and Sanderson[1] have studied Pb^{208} with RPA methods and except for the lowest 3-state, the agreement with recent experimental results is not too good. An attempt was made to improve the theoretical results by using a different residual force with a varying force strength. The residual forces used so far have not given any improvement over the work of Gillet, et al.[1] (W. W. True)

XIX. Study of Odd-Odd Nuclei in the A=120 Region

Work was continued with Leonard Kisslinger in a survey of the odd-odd nuclei in the A=120 region. The indium and antimony isotopes were studied most intensively. First, the neighboring odd-even and even-odd nuclei were studied using the quasi-particle techniques of Kisslinger and Sorensen.[2] Then the odd-odd nucleus was considered to be described by an even-even core around which moved a neutron quasi-particle and a proton quasi-particle which could interact with each other through a residual central force and by coupling to the L=2 phonon oscillations of the core. It appears that the singlet-even, triplet-even, singlet-odd, and triplet-odd components of the residual central force must be restricted to fairly well determined regions in order to obtain agreement with the experimental data available. (W. W. True)

1. V. Gillet, A. M. Green, and E. A. Sanderson, Nucl. Phys., 88, 321 (1966).
2. L. S. Kisslinger and R. A. Sorensen, Mat. Fys. Medd. Dan. Vid. Selsk. 32, no. 9 (1960).

XX. Particle-Phonon Coupling

Seven levels, I=3/2 - 15/2, in Bi^{209} around 2.6 MeV appear to be describable by coupling a 1h 9/2 proton to the 3- excited level at 2.6 MeV in Pb^{208}. In collaboration with C. Shakin and J. da Providencia, the 3- phonon state was assumed to be described by a RPA calculation, and the fine structure splitting of these levels in Bi^{209} was assumed to be due to the interaction between the $h_{9/2}$ proton and the 3- phonon. The theoretical details of the particle-phonon interaction were worked out and a computer program was written to calculate the fine structure splitting. The experimentally observed level ordering was not obtained and it is felt that a better description of the 3- phonon is needed. (W. W. True)

XXI. Static Nuclear Shapes in the Rare-earth Region

The potential energy of deformation, $V(\beta, \gamma)$ is calculated withe the Pairing-Plus-Quadrupole model for nuclei with N=82-126, Z=50-82. There is a sudden onset of deformation in the N=86-90 region, and the static nuclear shape, the lowest minimum of the potential function, changes from spherical to prolate. The disappearance of deformation in the Z=74-80 region is more gradual, and the static shape changes from prolate to asymmetric to oblate to spherical. The energy of zero-point motion is calculated, and it is concluded that all the stable deformed shapes of the region are prolate. Proton and neutron energy gaps, intrinsic quadrupole moments, moments of inertia, and gyromagnetic ratios of the even-even nuclei of the rare-earth region are calculated. Good agreement is obtained with experiment and many new values are predicted. (K. Kumar with M. Baranger)

XXII. Energy Levels and Electromagnetic Moments of the Tungsten, Osmium and Platinum Nuclei

The low-lying, even-parity energy levels and wavefunctions of the even isotopes of tungsten, osmium and platinum nuclei are calculated within the framework of Bohr's collective Hamiltonian. The six kinetic energy functions and the potential energy function which enter the Hamiltonian and which determine the coupling between rotational motion, β-vibrations and γ-vibrations are derived microscopically by using the Pairing-Plus-Quadrupole model of residual interactions. Couplings between the three kinds of motion are treated exactly, and a numerical method is used to solve the Schrodinger equation. At the low-A end of the W-Os-Pt region, there are large deviations from the Rotational model: the β-γ-bands are strongly mixed. At the high-A end, there are large deviations from the Phonon model: the wavefunctions are smeared over all possible shapes, and a large, positive quadrupole moment of the first 2+ state of ^{196}Pt is predicted. Many energy levels, B(E2) values, quadrupole moments, B(M1) values, magnetic moments, electric monopole transitions and nuclear shape fluctuations are also predicted. (K. Kumar with M. Baranger)

XXIII. The Static Quadrupole Moment of Vibrational, Even Nuclei and the Coupling Scheme for Odd Nuclei

The harmonic vibrational model, and its microscopic description by Kisslinger and Sorensen in terms of the pairing-plus-quadrupole model and QRPA, are modified so as to account for the large quadrupole moment of the first 2+ state of "spherical" nuclei. In this modification, based on the work of Baranger and Kumar, the lowest few nuclear states are described as linear combinations of phonon states. The needed admixtures are about 10% or less (essentially independent of A) and are such as to preserve the vibrational features, including a small cross-over branching ratio, $B(E2; 2' \rightarrow 0)/ B(E2; 2' \rightarrow 2)$. When an odd particle (quasi-particle) is coupled to these modified states and a KS type of calculation is performed, a considerably improved coupling scheme of odd nuclei is obtained. In the Copper (odd proton) and Nickel (odd neutron) regions, the density of low-lying levels, as well as many ground state spins (not given correctly by the KS calculation) are improved. (K. Kumar and L. Kisslinger)

XXIV. Numerical Solutions of Bohr's Collective Hamiltonian in the 5-D Oscillator Representation

In the completely numerical method of solving Bohr's collective Hamiltonian[1], the values of wave functions at the points of β-γ-mesh are used as variational parameters. Therefore, the matrix size depends on the number of points in the mesh, and hence the numerical accuracy is limited by the storage capacity of the available computer. We attempt to improve this method by expanding each nuclear wavefunction in the 5-dimensional $(\beta, \gamma, \theta, \phi, \psi)$ oscillator representation (equivalent to the phonon model representation). Integration over β and γ is still done numerically since the Hamiltonian is, in general, a complicated numerical function. However, the matrix size is now independent of mesh dimensions and depends only on the number of oscillator states (phonons) needed for a satisfactory convergence. This convergence is expected to be quite rapid, at least for the vibrational or transitional (not strongly-deformed) nuclei. A code has been written which generates the oscillator wavefunctions with $N \leq 9$, $I \leq 4$. It is expected that this modification will result in an improved numerical accuracy, as well as easier interpretation of the collective wavefunctions; but more work needs to be done. (K. Kumar)

1. K. Kumar and M. Baranger, Nucl. Phys. A92, 608 (1967).

XXV. Retarded Interactions in Fermi Systems

The nature of the two-body interactions in many fermion systems is studied from the viewpoint of meson theory. An exactly soluble model is formulated for linear coupling of a meson field to fermion density fluctuations, in which meson degrees of freedom are treated exactly, and fermion motion within the domain of the random phase approximation (RPA). Instability conditions for the RPA ground state are established. More generally, the effective two-body interaction is deduced via a Green's function technique by eliminating the meson degrees of freedom. This interaction is shown to be frequency dependent, i.e., retarded in time. The resulting interaction is then applied to the calculation of the Hartree-Fock field and the collective modes of the system via a generalized Landau equation. In the H.F. approximation, one obtains an unambiguous separation of renormalization (self-energy) effects and the nucleon-nucleon interactions themselves, the former reducing to the correct mass renormalization of the nucleon in the static limit. For reasonably small momenta ($p < p_F$), the retardation corrections to the H.F. field can be characterized by a small parameter $(\epsilon_F/\mu)^2$ ($\approx .1$ for actual nuclear densities), where ϵ_F = Fermi energy and μ = meson mass. The corrections become more important at high momenta and densities. In the long-wavelength limit, the frequency dependent corrections to the collective mode energies are found to be of order $(\omega/\mu)^2$, where ω = collective mode energy. For a static Yukawa interaction, a value $\lambda^2 \approx 5$ (consistent with the usual shell model values) is found for the neutral scalar coupling constant by requiring that the giant dipole collective state appear at the experimental energy. For pseudoscalar coupling, the usual renormalized coupling constant $f^2/4\pi \approx .08$ is shown to yield a "breathing mode" in heavy nuclei consistent with crude estimates based on nuclear compressibilities. (C. B. Dover and R. H. Lemmer)

XXVI. Calculation of the Nuclear Optical Potential

An attempt has been made to calculate the scattering of low energy nucleons from O^{16} using the Hartree-Fock potential generated with the Tabakin force. Second-order contributions to the potential are necessary in order to obtain a good S-wave phase shift. The role of nearby doorway states in the scattering is also under investigation. The Hartree-Fock potentials generated are of non-local character and a special iteration scheme has been developed for their solution. A paper is in preparation. (A. K. Kerman, A. D. MacKellar and J. Reading)

XXVII. An Extension of the Theory of Intermediate Structure

An extension of the intermediate model formalism is discussed, which applies to any scattering problem in which the entrance channel couples directly, not only to the doorway states but also to "compound nucleus" states. A detailed expression for the average scattering amplitude is obtained, and the consistency of the formalism is shown by proving that the condition $|<S>|^2 < 1$ is always satisfied. (F. Iachello)

XXVIII. Studies in Isobaric Analogues Resonances. II
Fine Structure

The properties of the fine structure observed in connection with isobaric analogue resonances in the elastic scattering of protons are examined in terms of the damping mechanism for the analogue state. The observed asymmetries of the strength function are shown to be associated to phase correlations between damping and escape amplitudes. Correlations of the necessary type will possibly result from the virtual coupling through the open channel between the analogue states and the nearby compound nucleus states of normal symmetry. A brief discussion of the possible role of doorway states in feeding the latter is also given. (A. F. R. de Toledo Piza and A. K. Kerman)

XXIX. Isobaric Analog States - Coupled Equations

The isobaric analog resonance corresponding to single particle states has been discussed using the coupled optical model proposed by Lane, and a reasonable fit to the experimental resonance is possible. However, it is known from stripping experiments that the single particle states are not pure and that the strength is spread among several levels. In order to include this effect a generalized form of the optical model was proposed in Phys. Rev. Letters, 17, 1184, (1966). This involves adding a separable non-local term into the optical potential. A code capable of handling such non-local coupling terms has been written by E. Bartels and attempts to fit the analogue resonances with spectrosocpic factors less than one are under way. (A. K. Kerman)

XXX. Calculation of Analog Resonances in Bi^{208}

The coupled channel system of euqations developed previously for investigating the resonance scattering of nucleus by nuclei is being used to calculate the widths and positions of expected analog resonances in Bi^{208}. Several of such states have been observed in $p + Pb^{207}$ scattering experiments. The present calculation attempts to describe the analog states as particle-hole excitations out of a Pb^{208} core that interact via a short range two-body force. We hope to learn something about the consistency of such a microscopic approach by attempting to fit energy levels and widths with a common interaction. (E. H. Auerbach, C. B. Dover, and R. H. Lemmer)

XXXI. Many Body Theory of Deuteron Stripping

The methods of many body perturbation theory are applied to the deuteron stripping reaction. It is shown that (except for recoil effects) the stripping amplitude can exactly be written as the matrix-element of a two body interaction in the form

$$T = S\, \phi_b(1) < \phi_R^{(-)}(2) | V(E) | \psi_K^{(+)}(12) >$$

ϕ_b being the H.F. orbital of the captured particle, $\phi_K^{(-)}$ the wave function of the outgoing nucleon in the G.O.P. of the target, and $\psi_K^{(+)}(12)$ a "deuteron like" state in the potential $(12|W(E)|1'2')$ discussed in section 3. V(E) is given as a power series in the nucleon-nucleon interaction. S is a spectroscopic factor. In lowest order in V(E), T is given by an expression akin to the usual D.W.B.A. (W. Junkin and F. Villars)

XXXII. The Generalized Optical Potential for Deuterons

The nucleon G.O.P. is a one body potential reproducing the elastic scattering amplitude for a nucleon-nucleus collision. Its approximate construction in terms of many-body perturbation theory is well known.

Following this technique, we have constructed a two-body potential operator $(12|W(E)|1'2')$, which properly describes (as a two body problem) the processes

$$(N,Z)_0 + D \rightarrow (N,Z)_0 + D'$$
$$(N,Z)_0 + D \rightarrow (N,Z)_0 + n' + p'$$

Eliminating the break-up channel, and integrating out the deuteron internal wave function leads to the deuteron G.O.P. $(R|W(E)|R')$. Our approach shows a transparent relation between the one-nucleon and the deuteron G.O.P: the leading terms in the latter being a convolution of the deuteron wave function and the sum of neutron and proton G.O.P. (W. Junkin and F. Villars)

XXXIII. Effects of the Pauli Principle in Deuteron Scattering and Stripping

The effect of the Pauli principle on the deuteron scattering and stripping reactions is being determined using the projection operator technique. Numerical evaluations are being made for a particular practical case. (L. Dohnert)

XXXIV. Nuclear Scattering in the Random Phase Approximation

A simple extension of the random phase approximation (RPA) is described that includes scattering channels of a single nucleon. Coupled equations are derived for the single nucleon amplitudes that describe the scattering states of the nucleon by an assembly of identical nucleons.

These equations reveal that the exclusion principle is taken into account by antisymmetrized interaction matrix elements plus the appearance of the projection operator $1 - \rho_0$ (ρ_0 is the single particle density) into unoccupied single particle states in the compound nucleus. The use of the RPA also introduces the effects of long range correlations, the well-known "backward going graphs" of many-body perturbation theory, in the scattering problem.

The system of equations thus obtained contains no parameters beyond those describing the two-body matrix elements that generate the Hartree-Fock field that serves as a zero order approximation to the excitations considered within the RPA. The scattering solutions of these equations are illustrated with a soluble model. It is shown that the presence of correlations in the wave functions of resonance states can influence their particle decay widths considerably. The important practical problem of angular momentum decomposition of the coupled equation system is also discussed. (R. H. Lemmer and M. Veneroni)

XXXV. Nucleon Correlations and Quasi-elastic Electron Scattering

Recent (e, e' p) experiments have been analyzed assuming that the scattering process is quasi-elastic (elastic scattering of the electron from a nucleon which recoils and is thus emitted). For such processes the angular distributions of the emitted protons is directly related to the momentum distributions of the various shells. The momentum distributions obtained in this manner are significantly different from those given by the usual shell models, and also appear to be inconsistent with the charge distribution obtained from elastic electron scattering. A preliminary investigation indicates that this discrepancy may be due to the neglect of nucleon-nucleon correlations which prevent such (e, e' p) processes from being purely quasi-elastic. More detailed investigations are now in progress.

XXXVI. High Energy Scattering Approximations with Application to Scattering from Vibrational Nuclei

It is shown that the high energy or Glauber approximation can be improved so as to be applicable at lower energies and larger angles. The range of validity of the Glauber and the improved approximations are determined numerically for a simple case. The approximations are applied to coupled channels vibrational nuclei and simple expressions are obtained for the elastic and inelastic scattering amplitudes. These were programmed and compared numerically. (W. Bassichis, H. Feshbach, J. F. Reading)

XXXVII. High Energy Proton-Deuteron Scattering

The work of the Brookhaven collaboration has determined the proton deuteron elastic scattering cross section over a wide range of angles. In particular, there is a strong peaking of the cross section at backward angles apparently due to a neutron pick up process. Calculations of this process using realistic deuteron wave functions in the impluse approximation seem to give a 1 BeV cross section at 180 degrees which is significantly lower than the experimental value. We have investigated the possibility that a small amount of nucleon isobar (1688) is present in the deuteron wave function. Calculations using one pion exchange terms indicate something in the neighborhood of 1/2% probability for this to happen. Because the (1688) is a $D_{5/2}$ nucleon resonance, it contributes to a second D-state in the detueron wave function and this leads to a large cross section in the pick up reaction, at 1 BeV without effecting the quadrupole moments or other static properties. Further work is in progress. (A. K. Kerman and L. Kisslinger)

XXXVIII. Multiple Scattering at High Energies

Present interpretations of 1 GeV nucleon-nucleus scattering has been made in terms of the Glauber approximation. This approximation neglects the off the energy shell contribution. The effect of these contributions is expected to be particularly important in the determination of nuclear correlations. They are now in the process of being evaluated. (A. K. Kerman and H. Feshbach)

XXXIX. Parity Nonconservation in Nuclear Interactions

The possibility of parity nonconservation in the interactions of strongly interacting non-strange particles is indicated by present theories of weak interactions. A model for the parity nonconserving portion of the two nucleon interaction has been developed based on the current-current model for weak interactions, and on conserved vector current theory. We have begun the work of applying this model to determine the parity violation to be expected in the process of radiative capture of thermal neutrons by deuterons, a process for which the violation may be large enough to observe experimentally. (J. F. Walker, H. Feshbach)

XL. Quark Model Predictions for Hadron Decays

The quark model is used consistently to calculate weak, strong and electromagnetic decay rates of the fundamental 36 meson multiplet and the 56 baryon multiplet of SU(6). Symmetry breaking effects are introduced through the assumption that the value of the quark-anti quark wave function of the mesons at zero distance is proportional to the square root of the meson mass.

Semi-leptonic weak decay rates are calculated from an effective Lagrangian of the current x current type, where the hadronic currents are the usual Cabbibo currents expressed in terms of quark fields. The quark model wave function used requires an F/D ratio of 2/3. The non-leptonic weak decay modes are calculated from pole type diagrams. The quark model is used there to evaluate the relevant coupling constants.

The strong decay modes are calculated from an effective Lagrangian which consists of a sum of current x current terms. The results are equivalent to previously obtained current algebra results. The elctromagnetic decay modes are calculated with the aid of the vector dominance assumption for the electromagnetic current. The quark model is used to calculate the relevant couplings which appear in the relativistic formulae for the decay widths. The predictions are compared with those of the integer-charge quark model of Cabbibo, Maiani and Preparata.

All predictions for the weak, strong and electromagnetic decay modes are in good agreement with experiment. (A. Dar and V. Weisskopf)

XLI. Symmetry Breaking Effects in the Quark Model from Weinberg's First Sum Rule Plus Asymptotic SU(3)

It is shown that the symmetry breaking effects in the quark model introduced through the assumption that the quark anti quark spatial wave function of a meson at zero distance is proportional to the square root of the meson mass, can be derived from Weinberg's first type sum rules combined with asymptotic SU(3) and vector dominance assumptions. (A. Dar and V. Weisskopf)

XLII. Weinberg Sum Rules and the Vector Dominance Assumption for the Electromagnetic Current

It is shown that if the vector dominance assumption for the electromagnetic current and the asymptotic SU(3) symmetry are good approximations then Weinberg's second sum rule is inconsistent with the mass spectrum of the vector mesons. On the other hand, the vector dominance assumption combined with Weinberg's first sum rule yields meson decay rates which are in good agreement with experiment. (A. Dar and V. Weisskopf)

XLIII. Electromagnetic Corrections to β Decay

The electromagnetic corrections to μ decay have been known for years to be finite, whereas the neutron decay appeared to be divergent. It had been hoped that the strong interactions would make the latter finite. We have shown that this is not in general the case. In particular, the conventional quark current algebra leaves a logarithmic divergence; however, a modified algebra, based on integrally charged triplets, is finite. Whether this should be taken seriously or not depends on the as yet not understood high energy structure of the weak interactions. (K. Johnson, F. E. Low and H. Suura)

XLIV. Possible Finite Radiative Correction to Weak Processes

Motivated by the recent consideration of Johnson, Low and Suura[1] the possibility of finite radiative correction (to order α) to the process $\mu \rightarrow e + V_\mu + \bar{V}_e$ is considered in the intermediate boson model. The EM vertex of the boson is assumed to have minimum momentum powers consistent with Ward identifies, with magnetic and electric dipole moments as free parameters. It is found that, besides renormalization effects, the divergences cannot be removed by adjusting free parameters. However, the divergences are universal if the lepton masses are taken to be zero. (M. Cassandro and P. K. Kuo)

XLV. Angular Momentum Branch Points in Proton-Proton Scattering

The logarithmic derivative of the cross section for 90° proton-proton scattering exhibits a sharp break at about 3.7 BeV (CM energy). It was shown that this feature is readily understood in terms of our present understanding of the complex angular momentum plane as a result of the interference between the Pomeranchon trajectory, and the Regge-Mandelstam branch point associated with two Pomeranchon trajectories. (C. E. Jones, K. Huang, V. L. Teplitz)

XLVI. Large-Angle p-p Scattering

It is shown that there is experimental evidence indicating that the vacuum trajectory alone dominates the cross section in the interval $0.5 < -t < 1$ $(\mathrm{BeV/c})^2$, with trajectory $\alpha(t) = 1 + 0.3t$. Assuming single Regge pole dominance, one can derive the empirical formula $d\sigma/dt = A \exp(-\lambda k^2 \sin\theta)$ for $\theta \approx 90°$. It results mainly from the definite relation between Regge poles in the t and the u channel, as required by the Pauli principle. (K. Huang and S. Pinsky)

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1. Johnson, Low and Suura, Phys. Rev. Letters 18, 224 (1967).

XLVII. Polarization as a Test for Regge Cuts

The exchange of the ρ meson Regge trajectory provides a satisfactory explanation of the angular distribution for the reaction $\pi^- + p \to \pi^0 + n$. However, this simple model does not explain the large and non-decreasing polarization at the lab energies 6 and 12 GeV. The exchange of one Regge trajectory would give zero polarization since the phases of the helicity flip and helicity non-flip amplitudes are the same.

It was shown that a Mandelstam-Regge branch point with the ℓ quantum number, which is expected to be present on theoretical grounds, yields a natural explanation of the polarization. (L. J. Muzinich and V. L. Teplitz with D. Gross and V. De Lany (Harvard))

XLVIII. Branch Points, Fixed Poles, and Falling Trajectories in the Complex J Plane

By means of the N/D equations, analytically continued in complex angular momentum, we consider the details of the mechanism by which cuts in the angular-momentum plane eliminate Gribov-Pomeranchuk singularities. The implications of the two-body unitarity requirement are investigated. A fixed ℓ-plane pole in the signatured partial-wave amplitude is shown to exist where the first Gribov-Pomeranchuk singularity would be expected in the absence of cuts. It is also shown in this case that moving (Regge) poles are not asymptotic to the position of the fixed pole. (C. E. Jones and V. L. Teplitz)

XLIX. Investigation of the Hypotheses of Khuri's Theorem on Regge Pole Asymptotes

A theorem of Khuri states that if (1) Regge pole residue functions are bounded by a certain exponential and (2) the trajectory function $\alpha(s)$ has no complex branch points, then $\alpha(s)$ must stay finite as s becomes infinite. We show that (1) is unreasonable because of Mandelstam's 1-plane symmetry and (2) is unreasonable in the presence of coupled channels. (C. E. Jones and V. L. Teplitz)

L. Conspiracy and Evasion in the Vector-Spin Model

There exists one known theory which is renormalizable and contains an elementary particle that lies on a Regge trajectory and this is the spinor-vector theory. What we are trying to do is to show how the mechanisms of conspiracy and evasion work in this model, which is ob-

viously soluble at the lowest order in perturbation theory (i.e., Born term). The work that is now in progress is about the translation into the language of the n-plane of the results in the J-plane. (M. Cassandro, I. Muzinich, V. I. Teplitz, with E. Abers)

LI. Conspiracy

The reactions $pn \to np$ and $p\bar{p} \to n\bar{n}$ near the forward direction are analyzed for evidence of "conspiracy". Using experimental data, all Regge pole conspiracy schemes involving the pion and at most one other conspiring family can be ruled out, under the assumption of constant residue functions. The data, on the other hand, is consistent with π exchange and conspiracies of branch cuts in the angular momentum plane. It is suggested that the relevant branch cuts are those arising from ρ-P and A_2-P exchange, where P is the vacuum trajectory. (K. Huang and I. J. Muzinich)

LII. Pole and Cut Conspiracy and Pion Photoproduction

The sharp forward peak observed[1] in high energy π^+ photoproduction is studied in terms of the Regge pole model. It is found that the data demands some type of conspiracy mechanism. A conspiracy among simple poles alone appears incompatible with the data. However, π-π' pole conspiracy plus a cut conspiracy is compatible with the data.[1] This mechanism appears indistinguishable from a mechanism which involves only cut conspiracy. (D. Gordon and J. Frøyland)

LIII. A Regge Model of High Energy π-Meson Photoproduction in the Forward and Backward Directions

In this thesis we study the photoproduction of single π-mesons in a Regge model, with special emphasis on some of the new developments, daughter trajectories and conspiracy conditions, in Regge theory. Throughout we use the helicity amplitude formalism. We re-examine the effects of gauge in invariance into the reggized amplitudes. We also investigate the asymptotic behavior of the amplitudes at $t=t_{forward}$ and $u=u_{backward}$.

We show that photoproduction by means of a polarized beam should be an excellent way to separate the contributions of the various meson trajectories and that it should provide a means

1. M. G. Buschhorn, et al., Phys. Rev. Letters 17, 1027 (1966), B. Richter, private communication.

of testing for the existence of a conspiracy at $t=0$. We demonstrate a new derivation of the conspiracy conditions for photoproduction using only the helicity amplitudes and their crossing properties and see that these conditions do not follow from conservation of angular momentum in the forward direction. (V. L. Teplitz and M. H. Vaughn)

LIV. Elastic Unitarity and Regge Cut Discontinuities

We examine the constraints imposed on Regge cut discontinuities by elastic unitarity. We find that discontinuities must be *singular* at their end-points, and, contrary to published examples, must vanish there. We give particular attention to "wrong signature" negative integer angular momenta in the spinless problem. There one Regge cut must exactly mask the elastic unitarity cut; its discontinuity *contains* a pole in the angular momentum. Our results modify the usual expression for the contribution of a cut to high energy scattering in crossed channels. (J. Bronzan and C. E. Jones)

LV. Super Convergence Relations in the Presence of Regge Cuts

In scattering amplitudes where there are high isotopic spin and high spin, it has been argued that helicity flip amplitudes corresponding to isotopic spin two *channels* should be super-convergent. The super-convergence relation follows from assumptions about Regge behavior and no subtractions in the scattering amplitude. Typically, if an amplitude has an asymptotic behavior in energy s of the form $s^{\alpha-1}$ where $\alpha < 0$ the amplitude should then be super-convergent. In the case of isotopic spin two such a super-convergent amplitude seems unlikely since even though there are no Regge trajectories with $\alpha > 0$, there are candidates for Regge cut trajectories with $\alpha > 0$. The cut associated with two rho meson Regge trajectories is such an example. (I. Muzinich)

LVI. Current Work on Multi-Regge-Pole Hypothesis

Current work is being done on the multi-Regge-pole hypothesis. Recent work at Berkeley based on Toller's variables, gives an unambiguous prescription for determining the asymptotic behavior of (2-particles) $\rightarrow$ (n particles) when various sub-energies are large. Under study is the question of what constraints are imposed by unitarity on the Regge parameters characterizing such asymptotic behavior. (C. E. Jones)

LVII. Current Algebra and Non-Regge Behavior of Weak Amplitudes

Certain weak amplitudes exhibit non-Reggistic behavior. These amplitudes have fixed poles in the complex angular-momentum plane which have the dual property of *allowing a sum* rule of the Dashen-Gell-Mann[1]-Fubini[2] type to hold, although one might naively expect a super-convergence[3] relation for this amplitude, <u>and</u> insuring that spin-one particle poles are reproduced correctly in the left-hand side of the sum rule. We demonstrate *the existence of the* fixed pole directly by comparing the sum rule with the Froissart-Gribov continuation to the complex J plane. We also study some models which exhibit this behavior. (J. B. Bronzan, I. S. Gerstein, B. W. Lee, and F. E. Low)

LVIII. High Energy Limit of Photon Scattering on Hadrons

In a class of models it was proven that quite generally fixed poles in angular momentum will exist at nonsense values *of both signatures*. The first model was an infinite subset of Feynman diagrams with charged photons interacting with a charged scalar nucleon (N) which in turn can interact with a scalar isoscalar meson (σ) Lagrangian of the form $N + N\sigma$. The second model employed unitarity for *the photon scattering* amplitude in a limited region of energy. It was shown that as a consequence of the absence of quadratic unitarity for a process treated to second order in the work on electromagnetic interactions that fixed poles will in general exist. One *effect of the fixed* pole *is* that the photoabsorption cross section on hadrons at infinite energy is finite. (F. E. Low and I. J. Muzinich)

LIX. Fixed Pole in Semi-Weak Processes

The existence of an analogous fixed pole in a semi-weak process (e.g., $\gamma + N \rightarrow \pi + N$) appears to imply elementarity of some intermediate final particle involved in the reaction. Experiments on high energy photo-pion production should reveal whether or not these poles exist. (G. Dosch, D. Gordon and F. E. Low)

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1. R. Dashen and M. Gell-Mann, in 1966 Coral Gables Conference on Symmetry Principles at High Energy (Freeman and Sone, San Francisco, 1966).
2. S. Fubini, Nuovo Cimento 43, 1 (1966).
3. V. de Alfaro, S. Fubini, G. Rossetti and G. Furlan, Phys. Letters <u>21</u>, 567 (1966).

LX. Fixed J Singularities for Axial Vector Currents

We are using the σ model of Gell-Mann and Levy[1] to study the existence of fixed poles in the complex angular momentum plane in weak amplitudes involving axial vector currents which satisfy PCAC. (I. Gerstein)

LXI. Properties of Coupled Channel Amplitudes

The analytic and asymptotic properties of amplitudes of strongly coupled channels have been investigated. To obtain quantitative estimates of qualitative properties, the boundary condition model is used to generate simple amplitudes with the required properties. Thus the effect of channel coupling on the movement of zeros of amplitudes towards the physical region is seen to make important contributions to phase shift dispersion relations. This invalidates the frequent use of the inelastic cut discontinuity as a sufficient measure of the effect of inelasticity on the phase shift. The development of complex C.D.D. singularities on coupling between more than two channels is studied. An infinite number of channels must be considered asymptotically in energy. Certain asymptotic distributions of channel thresholds are shown to permit regular asymptotic behavior even when the elastic approximation is highly singular there. An investigation of Regge cut trajectories in the multichannel case has been started. (E. L. Lomon)

LXII. π^+-π^- Mass Difference

We have applied the standard current algebra techniques, including the partially conserved axial current hypothesis, to the calculation of the π^+-π^0 mass difference. The agreement with experiment is remarkably good. (F. E. Low)

LXIII. Pion Electromagnetic Mass Difference for Physical Pions

We compute the on mass shell electromagnetic mass difference $M_{\pi^+} - M_{\pi^0}$, in a model consistent with chiral algebra constraints and PCAC, and find it to be logarithmically divergent. This calculation generalizes the result of Das[2], et al. (I. S. Gerstein, B. W. Lee, H. T. Nieh, and H. J. Schnitzer)

1. M. Gell-Mann and M. Levy, Nuovo Cim. 16, 705 (1960).
2. T. Das, G. S. Guralnik, V.S. Mathur, F.E. Low, and J.E. Young, Phys.Rev. Letters 18, 759 (1967).

LXIV. Pion Electromagnetic Mass Difference

We are studying whether the algebra of fields[1] predicts a finite result for $M_{\pi^+} - M_{\pi^0}$ to all orders in e^2 in the limit $M_\pi=0$. (I. S. Gerstein and H. J. Schnitzer)

LXV. Pion Nucleon Spin Flip Sum Rule

Current algebra and PCAC are used to derive a sum rule for the spin flip pion-nucleon scattering amplitude analogous to the Weisberger Adler sum rule for the non-spin flip amplitude. We find that such a sum rule requires information about the weak amplitude for axial vector-nucleon scattering in contrast to the V-A relation which requires no such information. As a by-product we give a decomposition of this weak amplitude into tensor covariants which is more useful than those previously appearing in the literature. This expansion applies to polar vector-nucleon scattering as well, and hence is relevant to Compton scattering. (I. S. Gerstein)

LXVI. Current Algebra Using Nucleon Targets

We are checking the experimental validity of the pion-nucleon spin flip sum rule derived previously.[2] We shall also apply the same techniques to an analysis of photoproduction and Compton scattering experiments. (I. S. Gerstein and W. Rybolt)

LXVII. Four Point Functions for Non-Soft Pions

We have extended the program of Weinberg[3] and Schnitzer and Weinberg[4] to a calculation of all four point functions of the vector and axial vector currents. Our results have the minimum momentum dependence consistent with the gauge constraints of chiral SU(2) x SU(2) and PCAC. We hope to generalize our work to n-point functions and to show how to include some effects of unitarity. (I. S. Gerstein and H. J. Schnitzer)

1. T. D. Lee, S. Weinberg and B. Zumino, Phys. Rev. Letters 18, 1029 (1967).
2. I. S. Gerstein, Phys. Rev. 161, 1631 (1967).
3. S. Weinberg, Phys. Rev. Letters 18, 507 (1967).
4. H. Schnitzer and S. Weinberg, Phys. Rev. (to be published).

LXVIII. Current Algebra Sum Rules for Arbitrary Spin and Mass

Current algebra sum rules for arbitrary spin and mass are obtained by extending a method developed by Fubini.

The well known complexity involved in expanding the T matrix in terms of Mandelstam invariants is avoided by using part tensor, part helicity amplitudes (mixed amplitudes).

It is found that current algebra demands that weak nonsense - strong sense helicity amplitudes have fixed poles, whereas weak nonsense - strong nonsense amplitudes have no fixed poles. Furthermore, for the vector-vector algebra, the positive parity conserving helicity nonsense-sense amplitudes enter into current algebra sum rules whereas the negative parity conserving nonsense - sense amplitudes superconverge. (D. Gordon and H. G. Dosch)

LXIX. Study of Applications of Current Algebra, PCAC, and Pole Dominance to Vertex Functions of the Current

Studies have been continued of the application of the assumptions of current algebra, PCAC, and pole dominance to vertex functions of the currents. It is found that a complete use of PCAC and current conservation requires the introduction of a subtraction in the dispersion relations for the invariant functions. for which current algebra yields low energy theorems.

The method is applied to the $A\rho\pi$ and $\rho\pi\pi$ vertices to obtain sum rules for the two $A\rho\pi$ coupling constants. The equations are consistent with the Kawaraboyasu-Suzuki relation for the axial vector two point spectral function, and predict $\Gamma(A \rightarrow \rho + \pi) = 60$ MeV and $g_T = -g_{LL}g^+, g_2$ the transverse and longitudinal $A\rho\pi$ couplings. The latter result disagrees strongly with the work of Gilman and Harari, who obtained $g=0$ by saturating $\pi\rho$ superconvergent relations. The result $-F_A = F\rho$ no longer follows in the new sum rules and the theoretical basis for this equality is shaky.

In light of the above results, the derivations of the Kawaraboyasu Suzuki relations are re-examined. It is found that there exists no unambiguous proof of this relation based on the assumptions of current algebra, PCAC, and pole dominance. From our $A\rho\pi$ sum rules we find that the approximate validity of the Kawaraboyasu-Suzuki relation is associated with the minimization of $g_T^2 + g_L^2$ and that the relation is exact for $F_A(g_T + g_L^2) = 0$. A summary of all these results will appear shortly in the Physical Review Letters.

Our work on vertex functions has been extended to the SU(3) x SU(3) algebra to obtain sum rules connecting the $A_K K^* \pi$, $\eta K \pi$ and $K^* K \pi$ vertices. A_k is the Y=1 axial vector meson and η is an assumed meson representing the I=1/2, s wave πK system. By giving up the assumption that the divergence of the strangeness changing vector current is partially conserved, i.e., $< p' | \partial^\mu V_\mu K | p > - 0, (p^1 - p)^2 \rightarrow \infty$, we obtain sum rules for $A_K K^* \pi$ consistent with present experiments. We obtain η widths, as well, which are much smaller than heretofore, and

consistent with the fact that no strong S wave $K\pi$ interaction has been observed. Our results for the η depend sensitively on symmetry breaking effects and are therefore quantiatively uncertain. Complete details of the work described in these three paragraphs will be submitted for publication in the near future.

We have investigated the current algebra-soft pion approach to the $\eta \rightarrow 3\pi$ amplitude. The work of Bardeen, Brown, Lee and Nick is re-examined for the more general case when the total momentum in the matrix element is not conserved. We find a linear expansion in the pion momenta of the same form as these authors, but our estimate of the magnitude of the amplitude, while ambiguous by a factor M_π / M_η, is smaller by at least a factor of 1/4. In our view, then, the relatively large magnitude of the $\eta \rightarrow 3\pi$ rate remains an unsolved problem. The soft pion limit does not appear to be relevant to the physical process. (D. A. Geffen)

LXX. Multiparticle Production in High-Energy Collisions

The "incoherent droplet" model proposed earlier is solved for the general case of muliparticle production. It predicts that the matrix element is a Gaussian in

$$\sum_{i=1}^{N} q_i^2 ,$$

where q_i is the transverse momentum of the ith final particle. The multiplicity is predicted to increase logarithmically with energy. (K. Huang)

LXXI. An Absorption Model Consistent with Unitarity

An absorption model consistent with unitarity is proposed for high energy two-body and quasi-two-body final state reactions. The model is free of some of the main difficulties of the Gottfried-Jackson absorption model. It is based also on the one particle exchange approximation but differs from the old absorption model in its prescription for calculating the attenuation coefficients for the partial wave Born helicity amplitudes. Preliminary predictions of the model for the identified two body and quasi two body final states production in K^+p collision at 3 GeV/c and in π^+P collision at 4 and 8 GeV/c are successful. (A. Dar, with C. E. Robinson, Columbia University)

LXXII. Absorption Enhancement of Symmetry Breaking Effects in High Energy Two Body Reactions

General principles of diffraction theory combined with the one particle exchange mechanism for high energy two body reactions are used to demonstrate absorption enhancement of symmetry breaking effects in two body and quasi two body productions. Quantitative predictions, derived for the photoproductions $\gamma + p \rightarrow \pi^0 + p$, $\pi^+ + n$, $K^+ + \Lambda$, $K^+ + \Sigma$ are in good agreement with experiment. (A. Dar and V. Weisskopf)

LXXIII. The K^+n S State Interaction and the K^+d Peak at 1.2 BeV/c

A peak has been found[1] in the K^+d interaction at 1.2 BeV/c, which can only be attributed to the I=0 K^+n interaction. A previous analysis[2] of K^+n data under 0.8 BeV/c indicated that the I=0 S state was coupled to the K^*N system in the $S_1/_2$ state. The parameters of the interaction were fixed by the analysis. We have extended the analysis to 1.5 BeV/c and have found that the previous model predicts a peak of the type observed. Small adjustments of the parameters permit a simultaneous fit to the low energy data and the newly observed structure. In this view the peak is a highly inelastic S state maximum, but does not achieve resonance in the sense of the amplitude describing a nearly complete circle in the complex plane. (E. Lomon and M. Krammer)

LXXIV. Vacuum Polarization in Quantum Electrodynamics

It is shown that if the photon propagator is set equal to $1/k^2$ in the expression for the vacuum polarization which is irreducible with respect to insertions in photon lines, then z_5' diverges like a single power of the logarithm of an ultraviolet cut-off in all orders of perturbation theory. The implication of this result upon the possible finiteness of ordinary quantum electrodynamics is discussed. (K. Johnson, M. Baker and R. Willey)

LXXV. Application of Conformal Symmetry to the Problem of Divergences in Quantum Electrodynamics

When the masses of the particles in renormalizable field theories vanish, the field equations are invariant with respect to scale transformations. The use of the so-called renormalization group is based upon this symmetry. The field equations in this limit are also

1. R. L. Cool, et al., Phys. Rev. Letters 17, 102 (1966).
2. W. J. deBonte and E. L. Lomon, Nuovo Cimento, 44A, 647 (1966).

invariant with respect to the "special conformal transformations". This symmetry is now under investigation with the hope that it can be used to simplify and extend calculations of the sort discussed under the above item. (K. Johnson and M. Baker)

LXXVI. Quantum Electrodynamics and Backward e^+-e^- Scattering

The perturbation series for the e^+-e^- scattering diverges at 180 degrees. Therefore its neighborhood is a good place to test high order effects of QED experimentally.[1] An analytic calculation to 4th order is carried out for this purpose. Preliminary analysis shows good agreement between theory and experiment. (P. K. Kuo, D. R. Yennie and A. Hearn)

LXXVII. Renoramlization in Perturbation Theory

The renormalization program within the framework of perturbation theory is re-formulated with an improved method. The essence of this method is to choose a universal subtraction point at the origin of the momentum space and to subtract "from-the-outside-in", i.e., subtractions are carried out to graphs then to subgraphs, in contrast with the method of Dyson and Salam. Practical aspects are also considered. (P. K. Kuo and D. R. Yennie)

LXXVIII. Two Photon Contributions to the Electron-Proton/ Positron-Proton Elastic Scattering Ratio

We are studying the ratio between electron-proton and positron-proton scattering at small momentum transfer. At present we are developing a formula which gives the ratio in terms of known radiative corrections and appropriate forward Compton scattering amplitudes for protons. (J. B. Bronzan and R. Brown)

LXXIX. High Energy Behavior of Feynman Graphs for Particles with Spin

Much interest has centered on the singularity structure of the scattering amplitude in the angular momentum plane and the consequent high energy behavior of the amplitude. Calculations in perturbation field theory for spinless theories has tended to justify the hypothesized Regge pole singularity structure. For theories with spin we developed, calculation techniques and topological rules by which one could read from the graph the high energy behavior directly.

1. A. Browman, B. Grossetete and D. Yount, Phys. Rev. 143, 899 (1966).

LXXX. Bethe-Salpeter Equation

The simple Bethe-Salpeter integral equation has such a singular kernel that it has been difficult in the elastic and production regions to either solve it numerically or to determine its mathematical properties. We use assumed spectral representations to reduce the equation to one where the kernel is compact. In particular we have used the Jost-Lehmann-Dyson representation and careful analysis shows that the singularities of the kernal are sufficiently tame to render the kernel compact. We have also used the spectral discontinuity in the energy of integration. There exists a Hölder space where this kernel is also compact. One can then use the well known theory of compact operators to determine the properties of the solution as a function of the coupling constant. (J. V. Greenman)

LXXXI. General Solutions of Static Models including Production

We studied the general two meson solution of the Lee and Charged Scalar static models. We investigated the nature of the arbitrary parameters in the solution to the dispersion relations for the V-θ sector of the Lee model and the charged scalar model in the two-meson approximation. Arbitrary functions are found to be present in the production and six-point amplitudes when CDD poles, corresponding to unstable particles, are allowed in the N-θ amplitude or the one-meson amplitude of the charged scalar model. The application of unitarity and other analyticity requirements shows that these arbitrary functions probably vanish in the Lee model. This is in contradiction to the claim of Luke that the arbitrary function in the production amplitude for $V^* + \theta \to V + \theta$ from the case where the unstable particle, V^*, is stable. The solution with the arbitrary functions zero is checked by analytic continuation to the stable case, where it gives the correct solution to the Low equations for that case. For the charged scalar model, unitarity is not sufficient to show the vanishing of these arbitrary functions, but analytic continuation to the stable case shows that it is consistent to take them equal to zero. An additional degree of freedom -- poles in a related function $f(\omega)$ -- is also investigated with the result that non-Herglotz poles of $f(\omega)$ are allowed unlike the situation with CDD poles which must be Herglotz. However, the non-Herglotz f-poles cannot give rise to new bound states of resonances. (J. B. Bronzan and M. Feinroth)

LXXXII. The Inclusion of Production in the Chew-Low Model

We studied the effects of three body states on the spin 1/2-isospin 1/2 channel in πN scattering[1]. We find that the three particle force is attractive, but not sufficiently so to produce

1. J. P. Le Brun, MIT Thesis, June 1967, unpublished.

the Roper resonance. Our model satisfies exact three particle unitarity. (J. B. Bronzan and J. P. Le Brun)

LXXXIII. Continuation in Complex Angular Momentum for a Three Body Equation

The particle bound state scattering amplitude in Amado's three body scattering model is continued in complex angular momentum for energies below the production threshold. The behavior of the leading trajectory in the left half ℓ-plane is studied. It is shown that, as argued by Mandelstam, the "compositeness" of the bound state allows the trajectory to pass through $\ell=-1$ and $\ell=-2$. (R. Aaron and V. L. Teplitz)

LXXXIV. A Phenomenological Approach to the Correspondence between Composite Systems and Elementary Particles

The Goldberger-Treiman relation is re-examined, based on a model in which pion is composed of a nucleon pair. As to the self-interaction of nucleon field, only the invariance under the local gauge transformations in iso-space and chiral iso-space is assumed. The relation can be reproduced to a fairly good approximation by a correspondence between a composite system and an elementary particle. The correspondence is phenomenological and not firmly established yet, but expected to shed some light on the correspondence problem. Because an important difference between a composite sytem and an elementary particle is revealed through the analysis.

This is an attempt to understand field-theoretically the powerful working hypothesis, the current algebra and the hypothesis of partially conserved axial-vector current, although some phenomenological arguments are unavoidable in settling a correspondence relation between a composite system and an elementary particle.

If we are contented with some approximations or some special types of interactions, we can consider various kinds of correspondences between composite systems and elementary particles. Two examples of such correspondence methods are examined. (T. Okabayashi)

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Prof. H. Feshbach
Prof. R. I. Hulsizer, Jr.
Prof. E. Lyon
Prof. L. Rosenson

Reading Room Committee

Prof. B. T. Feld, chairman
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B. Bailey
B. Wadsworth
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Headquarters

Prof. P. T. Demos Director	R. Gustavson Machine Shop
Dr. F.J. Eppling Associate Director	Miss. L. O. Leighton Reading Room
R. L. Loria Headquarters	P. Reardon Project manager, Linac
B. Bailey Engineering	J. L. Sargeant Purchasing
R. W. Calileo General Services	A. J. Scully Accounting
E. DeAgazio Electronics Shop	S. A. Tardivo Property
C. Frank Statistical Services	C. W. Tourtellotte Drafting

RESEARCH GROUPS **

COSMIC RAY GROUP

Research Staff	Visiting Staff	Graduate Students	Undergraduate Students
Dr. J. H. Binsack	Dr. R. L. Carovillano	J. K. Chao	F. H. E. Allegra
Prof. H. V. Bradt	Boston College	J. D. Dodson	T. H. Applebaum
Prof. H. S. Bridge	*Dr. A. Finzi	F. W. Floyd, Jr.	J. C. Backler
Prof. G. W. Clark	University of Rome	L. S. Glass	R. J. Borken
Dr. J. M. Davis	Dr. V. Formisano	G. R. Gilbert	J. L. Fields
Dr. M. Forman	University of Rome	B. E. Goldstein	A. M. Goldberg
Prof. G. Garmire (on leave)	Dr. S. Naranan	H. C. Howe, Jr.	D. B. Hill
Dr. A. S. Krieger	Tata Institute	K. A. Kolling	G. A. Minagawa
Prof. A. J. Lazarus	***Dr. L. G. Pai	K.-C. C. Leong	D. W. Seldin
Prof. W. H. G. Lewin	Physical Research	W. F. Mayer, Jr.	S. J. Sydoriak
Dr. J. Linsley	Institute, Ahmedabad	J. E. McClintock	
Dr. E. F. Lyon	Dr. M. V. Rao	G. A. Miller	
Dr. R. McKinnis	Tata Institute	G. M. Polucci	
Prof. S. Olbert	Dr. G. Spada	S. A. Rappaport	
Prof. J. W. Overbeck	University of Rome	G. R. Ricker, Jr.	
Prof. B. B. Rossi	**Technical Staff**	J. A. Stein	
Prof. H. W. Schnopper	T. W. Dawson	R. J. Sullivan	
Prof. G. L. Siscoe	E. A. Boughan	H. D. Tananbaum	
Prof. V. M. Vasyliunas	W. R. Shaw	R. I. Thompson	
Dr. C. G. Wang	W. B. Smith	J. M. Turner	
		E. A. Womack, Jr.	

* Terminated

** Research Staff: staff members participating full-time or part-time in LNS Researches and holding formal appointments either in MIT's Physics Department or in LNS as research staff members.

Visiting Staff: research staff members holding a formal appointment in LNS as a research staff visitor.

*** Deceased.

ACCELERATOR PHYSICS COLLABORATION

Research Staff	Visiting Staff	Graduate Students	Undergraduate Students
Dr. P. Bastien	*Prof. Y. Eisenberg	*I. Asher	L. Bachmann
*Dr. B. Brabson	*Dr. L. Fornasiero	D. Barton	B. Blumenfeld
* C. Brooks	*Prof. L. Guerriero	D. Brick	E. Colmer
Prof. B. T. Feld	Dr. C. Ouannes	L. Kirkpatrick	W. Graves
Prof. R. Hulsizer	Dr. M. Raijmakers	M. Marx	P. Langacker
Dr. V. Kistiakowsky	Dr. E. Ronat	B. Nelson	L. Smith
Prof. D. Miller	*Dr. J. Schotanus	H. Pradhan	L. Stutte
Prof. I. Pless	Dr. Y. Sokolowsky	A. Sheng	
Prof. L. Rosenson	*Dr. L. Ventura	J. Smith	
Mr. B. Wadsworth	Dr. F. Waldner	R. Thern	
Prof. T. Watts		F. Winkelmann	
		J. Wolfson	

LINEAR ACCELERATOR GROUP

Research Staff	New Linac Facility	Graduate Students	Undergraduate Students
Prof. P. T. Demos	P. Reardon (Project Manager)	N. Ensslin	*J. Bower
Prof. W. Bertozzi	F. Brooks	P. Hallowell	*D. Chang
Prof. S. B. Kowalski	J. Gano	*F. Hanser	
Dr. C. P. Sargent	J. Haimson	X. Maruyama	
Dr. W. E. Turchinetz	R. Johnson	M. Hussein	
Dr. C. F. Williamson	R. Keating	*J. Matthews	
	B. Mecklenberg	J. Bergstrom	
	J. Weaver	*T. Phillips	
		M. Zombeck	

HIGH ENERGY ACCELERATOR PHYSICS GROUP

Research Staff	Technical Staff	Graduate Students	Undergraduate Students
Prof. L. S. Osborne	G. C. Bolon	D. Bellenger	
Prof. R. A. Alvarez	D. Brothers	R. Bordelon	
Dr. K. Cohen		G. Cooperstein	
Dr. R. Lanza		S. Deutsch	
Dr. W. Lobar		K. Kalata	
Dr. P. D. Luckey		A. Nakkasyan	
		J. M. Onorato	
		R. Schwitters	
Prof. D. H. Frisch	E. Bonis	J. Alspector	
E. Druek		O. Fackler	
L. Stinson		D. Fox	
C. Strumski		S. Gray	
		J. Kasper	
		J. Martin	
		C. Nelson	
		E. Shibata	
		S. Smith	
		G. Smoot	
		L. Sompayrac	

* Terminated

HIGH ENERGY ACCELERATOR PHYSICS (continued)

Research Staff	Technical Staff	Graduate Students	Undergraduate Students
Prof. L. Rosenson		D. Barton	
		M. Marx	
		B. Nelson	
		R. Thern	
Prof. M. Deutsch	R. de Grazia	J. Cleetus	T. Jack
Prof. P. Patel	*R. Peterson	D. Friedell	*M. Levenson
Dr. K. Tsipis		L. Golub	J. Melson
		D. Potter	K. Marko
		L. Wilson	*D. Potter
			*J. Ritsko
Prof. J. L. Friedman	D. Dubin	M. Breidenbach	
Prof. H. W. Kendall	E. Miller	R. Ditzler	
Dr. G. Hartmann		J. Elias	
Dr. R. E. Shafer		P. Kirk	
		S. Poucher	
		M. Sogard	
		R. Temkin	

ONR GENERATOR GROUP

Research Staff	Visiting Staff	Graduate Students	Undergraduate Students
Prof. W. W. Buechner	*Dr. A. Graue	F. T. Dao	D. E. Bainum
Prof. H. A. Enge	University of Bergen	T. J. Fitzgerald	*L. E. Evans
Prof. T. A. Belote	Bergen, Norway	H. A. Ismail	R. R. Doering
Prof. W. E. Dorenbusch		L. L. Lynn	R. Harveyluk
*Prof. J. Kuperus	**Technical Staff**	*G. Nair	*H. Iuzzolino
Prof. W. H. Moore	H. Y. Chen	*N. M. Rao	*S. L. O'Dell
Prof. J. Rapaport	M. K. Salomaa	*B. J. O'Brien	*W. Patterson
Prof. E. R. Cosman		D. C. Slater	A. M. Paul
Dr. F. J. Eppling		*D. L. Smith	*Gail J. Pruss
A. Sperduto		J. E. Spencer	*J. W. Reynolds
		Mrs. Helen J. Young	*D. N. Schramm
			*J. S. Warniak
			B. H. Schwab

RADIOACTIVITY GROUP

Research Staff	Graduate Students	Undergraduate Students
Prof. L. Grodzins	*J. Alonso	*S. Berger
Dr. R. Kalish	E. Ansaldo	G. Brooks
*Dr. D. Murnick	M. Friedlander	P. Colter
Dr. J. Alonso	D. Perlman	*F. Flasar
Visiting Staff	*G. Pramila	*M. Schwarzkopf
Dr. J. Triff	C. Travis	*J. Udinsky
	*D. Yeboah-Amankwah	

* Terminated

CYCLOTRON GROUP

Research Staff	Visiting Staff	Graduate Students	Undergraduate Students
Prof. A. M. Bernstein	Dr. J. Alster	Y. C. Cho	M. Buck
Prof. W. J. Kossler		M. Duffy	*B. Cox
Dr. C. Moazed	**Technical Staff**	W. P. Liebowitz	*W. Ewing
	F. Fay	*E. Martens	A. Guth
	T. Provost	W. A. Seidler	T. Dininio
	E. F. White	*M. Slade	*L. Kuhn
		S. Smith	*E. Shalom
		J. Winkler	*M. Weissberger

THEORETICAL GROUP

Research Staff	Visiting Staff	Graduate Students	
Prof. W. V. Bassichis	*Dr. J. Froyland	J. Alderstein	E. Kujawski
Prof. J. Bronzan	Lokkwn	E. Ansaldo	J. P. Lebrun
*Dr. M. Cassandro	Farsund, Norway	H. Auerbach	P. Lee
Dr. L. N. Chang	*Dr. D. A. Geffen	E. Belasco	M. Marx
*Dr. J. da Providencia	Univ. of Minn.	S. Berger	F. Paige
Dr. A. Dar	Dr. R. D. Gordon	M. Best	H. Partovi
Dr. T. de Forest	*Dr. L. S. Kisslinger	A. Bhattacharyya	R. Peccei
Dr. H. G. Dosch	Western Reserve	M. Blackmon	S. Pinsky
Prof. H. Feshbach	*Dr. I. J. Muzinich	C. Brealey	E. Poggio
Prof. S. Fubini	Rockefeller Univ.	K. Brecher	E. Redish
Dr. T. Gaisser	Prof. F. Salzman	R. Brown	C. Rinehart
Dr. A. Gal	*Dr. W. True	R. Bruno	N. Rogerson
Prof. I. Gerstein	Univ. of Calif. at	E. Chalbaud	S. Roth
Dr. J. N. Ginocchio	Davis	L. Chang	B. Rouben
*Dr. J. Greenman	Prof. S. Weinberg	G. Chu	A. Rubenstein
Prof. K. Huang	*Dr. J. Weneser	G. Cooper	I. Rubenzahl
Dr. J. Hüfner	Brookhaven Nat. Lab.	L. Dohnert-Hueck	W. Rybolt
Prof. K. Johnson		G. Donner	L. Saunders
Prof. C. E. Jones		C. Dover	E. Schreier
Prof. A. Kerman		D. Ernst	H. Seigel
*Dr. K. Kumar		M. Feigenbaum	S. Sen
Dr. P. K. Kuo		M. Feinroth	D. Shapero
Prof. R. Lemmer		D. Freeman	J. Sharefkin
Dr. B. Levy		K. Friedman	R. Shea
Prof. E. Lomon		M. Fry	M. Strayer
Prof. F. Low		S. Galley	R. Stuller
*Dr. A. D. MacKellar		J. Goldstein	U. Sukhatme
Dr. T. Okabayashi		S. Hirschi	E. Thorsos
Dr. A. C. Phillips		R. Hobbs	F. Triantafyllidis
Dr. K. F. Ratcliff		L. Hubbard	M. Vaughn
Dr. R. V. Reid		F. Iachello	R. Vickson
Dr. D. Sachs		J. Jaffe	G. Weinberger
Prof. C. Shakin		W. Junkin	C. Whiteney
Prof. V. Teplitz		R. Keller	K. Witzke
*Dr. S. Tewari		A. Khakpour	R. Yaea
Dr. J. Trefil		S. Klawansky	R. Zia
Prof. F. Villars		M. Koren	
Dr. J. F. Walker, Jr.			
Prof. V. F. Weisskopf			

*Terminated